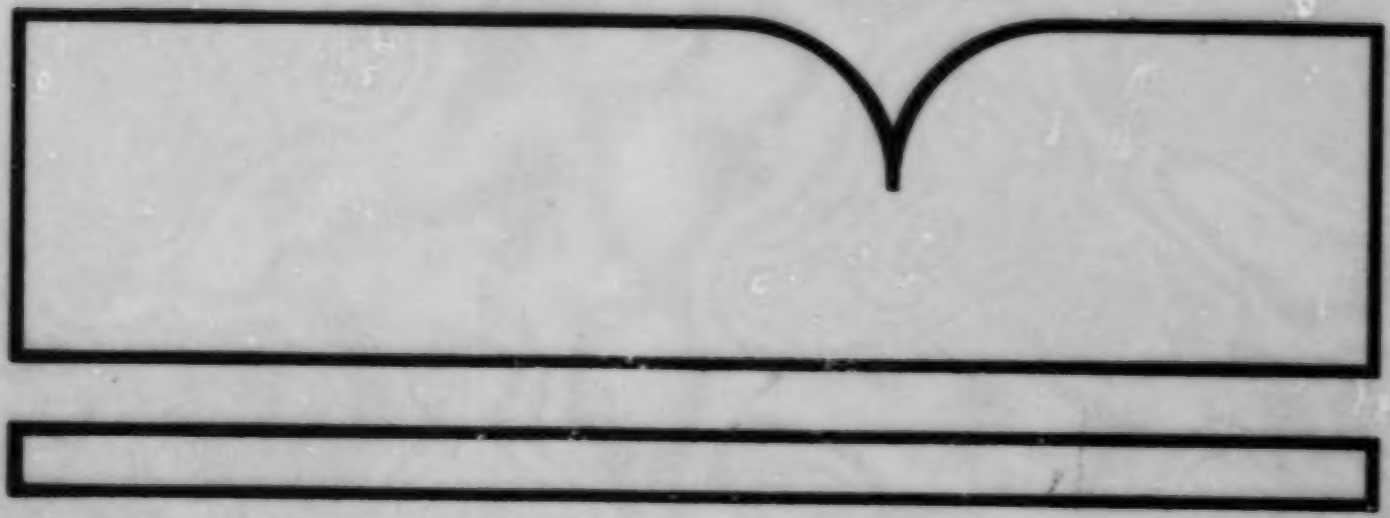
PB85-134377

Automated TEM (Transverse Electromagnetic) Cell Calibration System

(U.S.) Office of Radiation Programs
Las Vegas Facility, NV

Oct 84



U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Office of Radiation
P.O. Box 18416
Las Vegas NV 89114-5027

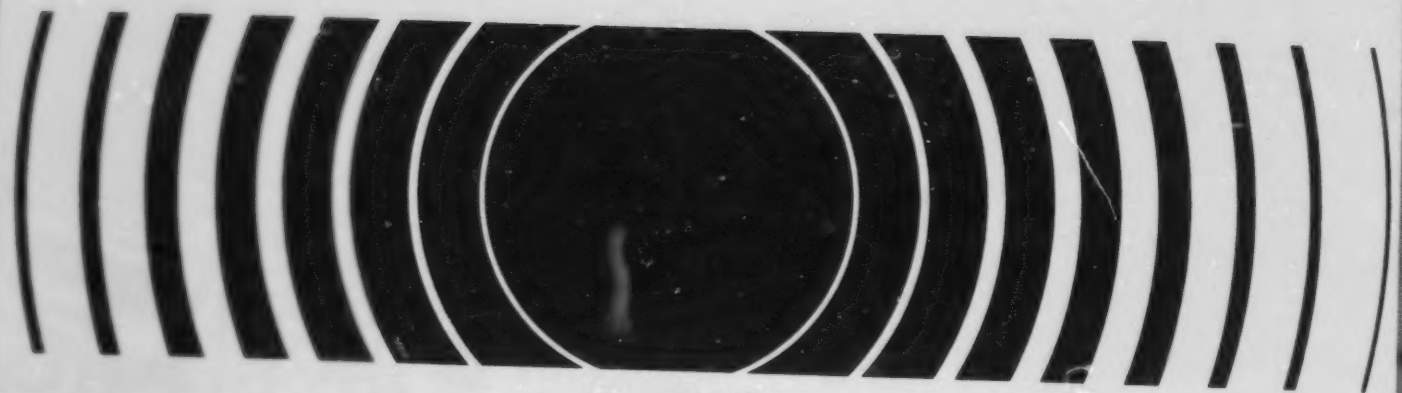
EPA 520/1-84-024
October 1984

Radiation

PB85-134377

EPA

An Automated TEM Cell Calibration System



REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
520/1-84-024		PB85 154377

4. TITLE AND SUBTITLE
An Automated TEM Cell Calibration System

5. REPORT DATE
October 1984

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Edwin D. Mantiply

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report discusses an automated TEM cell calibration system. It documents the field strength expressions applied, theoretical and experimental determination of modal characteristics of the two cells used, measurements of calibration parameters of system components, a system description, system testing, and sample applications of the automated TEM cell calibration system.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
unlimited	unclassified	112
	20. SECURITY CLASS *(This page)* unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

AN AUTOMATED TEM CELL CALIBRATION SYSTEM

Edwin D. Mantiply

October 1984

U.S. Environmental Protection Agency
Office of Radiation Programs
Nonionizing Radiation Branch
P.O. Box 18416
Las Vegas, Nevada 89114

DISCLAIMER

This report has been reviewed by the Office of Radiation Programs, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency, Nonionizing Radiation Branch develops Federal Guidance on acceptable environmental exposure levels of electromagnetic radiofrequency radiation and conducts an environmental assessment program. These functions require, among other things, determining the availability of accurate instrumentation to measure electromagnetic field strengths and thus, the performance evaluation of commercial and experimental hazard instruments. This report documents an automated transverse electromagnetic (TEM) cell system which is used to evaluate broadband radiofrequency survey meters.

Office of Radiation Programs

ABSTRACT

A design and evaluation project was initiated with the overall objective of creating an automated transverse electromagnetic (TEM) cell electromagnetic field calibration system. This system has been constructed at the Environmental Protection Agency to evaluate the performance of commerical and experimental probes which are used to determine environmental electric and magnetic field strengths. The TEM cell calibration system is composed of computer controlled signal generators, TEM cells, high power attenuators, computer read power meters, and probe rotation and data acquisition hardware. It is capable of producing highly accurate radiofrequency (RF) fields in the frequency range of 10 kHz to 220 MHz with root-mean-square electric and magnetic field strengths of up to 2000 volts per meter and 5.3 amperes per meter respectively.

Expressions for the electric and magnetic fields at the test location in the cells were developed which account for the effect of an imperfectly matched load and the resultant reflected wave, assuming the TEM cells are uniform transmission lines. These expressions are then generalized throughout a vertical cross section of the cell for the TEM mode of operation. Measurements were made of higher order TE and TM mode resonant frequencies, field strengths, and return losses for the two cells included in the system. Measured parameters were compared with theoretical calculations to predict resonant frequencies.

An error analysis of the various measured calibration parameters is presented. These errors are propagated through the equation for field strength to give the probable error in establishing field strength. Generator noise and harmonic distortion are also treated in the system evaluation.

System configuration, software control, and operation are documented to show how frequency, field strength, and probe rotation are controlled. Sample representative applications of the system and sample results obtained from tests of RF measurement probes are given.

CONTENTS

Foreword iii

Abstract iv

Contents v

Figures vi

Tables viii

Acknowledgment ix

1. Introduction 1

2. Conclusions and Recommendations 2

3. System Description 4

Configuration 4
Software development and operation 5

4. Basic Field Strength Expressions and Modal Characteristics of TEM cells 8
TEM fields at the test point in a TEM cell with reflections . 8
TEM fields throughout the TEM cell cross section 19
Modal characteristics of TEM cells 23

5. Calibration Parameter Measurements and Error Propagation . . . 44

Cell characteristics 44
Load characteristics 49
Power meters 53
Signal purity 54
Error propagation 57

6. Testing and Sample Applications 60

Comparison of probe response with and without impedance correction 60
Comparison of probe response using two different TEM cells . 60
Probe orientation changes 64
Probe potential sensitivity 65
Modal effects in large cell 67

References 68

Appendices

A. Load impedance program 70
B. System operating program 77
C. Detailed system diagrams 95
D. Probe calibration results compared with and without load impedance correction 99

Figures

Number		Page
1	TEM cell calibration system block diagram	4
2	System computer control structure	6
3	Configuration of a circular air coax	9
4	Cross-sectional geometry of a TEM cell	11
5	Standing-wave error as a function of reflection parameters	15
6	Squares of electric and magnetic field for a shorted CC-105 cell	18
7	Squares of electric and magnetic field for a shorted CC-101.5 cell	18
8	Squares of electric and magnetic field for an open CC-105 cell	18
9	Squares of electric and magnetic field for an open CC-101.5 cell	18
10	Cross section through the center of a TEM cell with coordinate system shown.	20
11	Field magnitude extremes for the CC-105 cell	20
12	Field magnitude extremes for the CC-101.5 cell	20
13	Normalized field strength IFI CC-105 TEM cell	22
14	Normalized field strength IFI CC-101.5 TEM cell	22
15	Effective lengths defined	27
16	CC-105 cell TE cutoff frequencies, range of resonant frequencies, and observed resonant frequencies	28
17	CC-101.5 cell TE cutoff frequencies, range of resonant frequencies, and observed resonant frequencies	28
18	CC-105 cell TM cutoff frequencies, range of resonant frequencies, and observed resonant frequencies	29
19	CC-101.5 cell TM cutoff frequencies, range of resonant frequencies, and observed resonant frequencies	29
20	Modal measurement system block diagram	31
21	CC-101.5 cell TE measurements	35-36
22	CC-105 cell TE measurements	38-39
23	CC-101.5 cell TM measurements	41
24	CC-105 cell TM measurements	41
25	Isotropic probe measurement of TE_{011} resonance	43
26	Cross sectional dimensions of the CC-101.5 cell	45

27 Cross sectional dimensions of the CC-105 cell 45
28 CC-101.5 cell dimensions 46
29 CC-105 cell lengths 46
30 CC-101.5 time domain reflectometry measurement 48
31 CC-105 time domain reflectometry measurement 48
32 Attenuation characteristics of high power load system 51
33 Load impedance 53
34 Time domain noise at 100 watt output 55
35 Frequency domain noise at 100 watt output 56
36 Time domain noise at 1 kW output 56
37 Frequency domain noise at 1 kW output 57
38 Field strength probe response without impedance correction 61
39 Field strength probe response with impedance correction 61
40 Field strength probe response in large cell 62
41 Field strength probe response in small cell 63
42 Field strength probe potential sensitivity 66
43 Modal effects in CC-101.5 cell 67

TABLES

Number		Page
1	Lower order TE_{mn} or TM_{mn} modes	24
2	Predicted TE cutoff frequencies	25
3	Predicted TM cutoff frequencies	26
4	Magnetic field probe calibration	32
5	Electric field probe calibration	33
6	CC-101.5 Cell TE measurements	37
7	CC-105 Cell TE measurements	40
8	Characteristic impedance	49
9	Probe orientation changes	65

ACKNOWLEDGMENTS

I would like to thank M. R. Molony for his programming assistance and program documentation. Graciela Martucci was of great help in editing this report. M. L. Crawford, C. M. Weil, D. A. Hill, S. J. Allen, P. C. Gailey, and R. A. Tell provided many useful review comments on an initial draft of this document.

SECTION 1
INTRODUCTION

Several different broadband electromagnetic (EM) radiation hazard survey meters have been commercially produced or built as prototypes by government laboratories. Field experience with some of these instruments has revealed the need for determining their absolute calibration and evaluating their general operation in radiofrequency (RF) fields.

Interaction with various government and industrial workers has led to EPA's use of three approaches to RF calibration: transverse electromagnetic (TEM) cells, waveguides, and standard gain horn anechoic ranges. All three of these approaches have been previously used by others with varying degrees of uncertainty in the calibration results. Apparently the greatest uncertainty results from the use of waveguide systems. Depending on the size of TEM cell, waveguide, or horn antennas used, the systems can overlap in frequency with physical size inversely proportional to frequency.

This report discusses an automated TEM cell RF calibration system. It documents the field strength expressions applied, theoretical and experimental determination of modal characteristics of the two cells used, measurements of calibration parameters of system components, a system description, system testing, and sample applications of the automated TEM cell calibration system.

SECTION 2
CONCLUSIONS AND RECOMMENDATIONS

An automated TEM cell electromagnetic field generation system was constructed from commercially available components. This system is particularly useful and flexible for performing isotropic field strength probe evaluations. The system can compensate for significant standing wave errors which would be impractical to perform manually. Fitted curves and interpolation for load attenuation and input impedance allow the choice of any frequency in the operating range of 10kHz to 220MHz so that narrow-band characteristics or resonances of field strength probes can be easily examined. The wide dynamic range makes possible the evaluation of probes at any field level of interest up to 2000 V/m electric field or 5.3 A/m magnetic field. The system can be setup by technicians to run unattended through any valid set of frequencies at a given field strength. Upon completion, the system generates and stores uniform reports of calibration.

The system configuration should continue to evolve. The upper frequency limit may be increased by implementing a smaller cell and higher frequency loads and amplifiers. Polar plotting routines have been implemented for probe rotation data. Because of the temperature coefficient of the attenuation system, a high power directional coupler as opposed to an attenuator to measure power should be considered. Finally, eliminating the cable between the load and cell would make the load impedance more stable.

Expressions for the field strength in the cell including the effect of reflections were derived. A comparison of probe calibration data obtained using these expressions and using the simpler expressions which assume no reflection from the load resulted in the conclusion that a useful increase in accuracy is acheived by using the more complex formulas. Even if the load were exactly 50 ohms resistive there would be standing wave error if the cell characteristic impedance were not also 50 ohms.

TEM cells can be used in an open or short circuit configuration with a directional coupler to gencrate known high or low wave impedance fields by applying formulas derived in this report.

The high frequency resonant characteristics of the two TEM cells used were measured and modeled. The lowest frequency resonance for the Instruments for Industry (IFI) model CC-105 cell was observed at 320 MHz and at 120 MHz for the CC-101.5 cell. High power low pass filters are used to reduce harmonics above these frequencies. Future work toward a more complete theory may involve numerical solutions to the three-dimensional theoretical problem of the cell viewed as a resonant cavity using moment methods; see for example [1,2].

The absolute probable error in the field strength at the test point including effects of reflections was determined to be ±0.79 dB for single mode (TEM) operation. Variations in the field away from the test point are given by theory, with a practical upper limit of ±0.4 dB.

A field strength probe was tested in both cells which resulted in readings typically 0.2 dB higher in the smaller cell. The increase was probably due to the loading effect of the probe.

Below approximately 10 MHz a problem was observed in which the entire field strength measuring instrument appears to act as an antenna or alternatively the instrument senses the potential difference between the meter and probe. This problem was termed "potential sensitivity" in reference to potential probes commonly used near 60 Hz power transmission lines. This problem makes some meters practically useless near standard AM broadcast transmitters. A solution in this situation is to use a meter having its antenna and readout in a single chassis.

More extensive testing of available meters will result in needed data on probe measurement accuracy and operational problems. This testing must include field work to document operational problems unique to the real world environment.

SECTION 3
SYSTEM DESCRIPTION

The automated TEM cell system built by EPA is a convenient, accurate system for establishing CW electromagnetic fields in the frequency range 10 kHz to 220 MHz. The frequency limitation is that of the linear amplifier used; the TEM cells can be set up manually above and below this frequency range.

CONFIGURATION

A block diagram showing the basic system configuration is given in Figure 1. Two different synthesizers are used and are selected under program control; the synthesizer output power and frequency are also under program control. The linear amplifier has two outputs which are manually selected, the low-level (100 watt) output is used up to about 30 watts and the final section is used from about 30 watts to its maximum output of 1 to 2 kW depending on frequency. Two commercially available TEM cells are used, a larger one, an Instruments for Industry (IFI) model CC-101.5 with a measured first resonance at 120 MHz and a smaller cell (IFI model CC-105) having less uniform fields over a survey probe's volume but an upper frequency limit of 320 MHz where the first resonance occurs. The plate separation, characteristic impedance, and electrical length are the

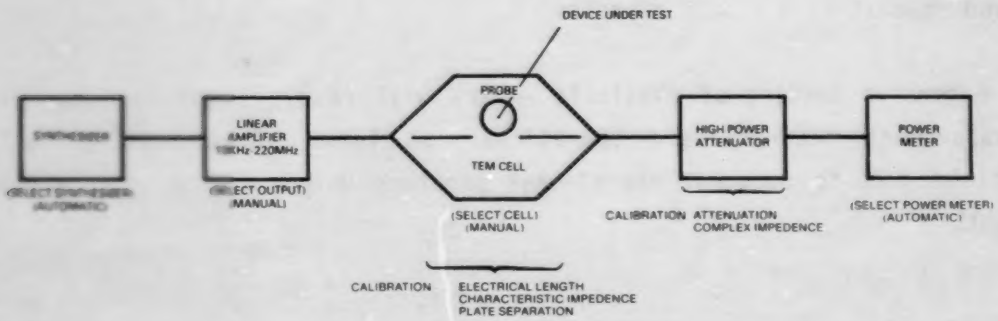


Figure 1. TEM cell calibration system block diagram.

important calibration parameters of the TEM cells and are stored in the operating program. A 2 kW attenuator of about 43 dB is constructed of a high power coaxial cable, a 2 kW 30 dB attenuator, 20 feet of RG-214/U cable, and a 13 dB low-power attenuator. The calibration parameters of the cable-attenuator (load) system are the total attenuation A and complex input impedance Z_1 which are stored in the program as a function of frequency. Finally three different power meters are selected by the computer, depending on the specified power level and frequency.

SOFTWARE DEVELOPMENT AND OPERATION

Figure 2 gives an overview of the control structure through which the computer can control and/or read the synthesizers, power meters, probe rotator, and hazard meter recorder output. The synthesizer, power meters, and printer are interfaced directly through the IEEE-488 interface bus. An analog to digital converter (ADC) on the bus is used to read the hazard meter output and determine the angular position of the probe rotator. A bus relay actuator is used to control the rotator motor and to operate a microwave switch to select power meters. A VHF switch on the bus selects the synthesizer. Detailed system diagrams are contained in Appendix C. Appendix B is a listing of the system operating program called "CELLGO" written in BASIC. The program is divided into five basic components, each of which may be somewhat independent of the other. Comments at the beginning of the program give the bus addresses of the various instruments used. A select code of 7 is always used, for example,

```
OUTPUT 722, "A1"
```

is a command to address 22, the VHF switch.

The program first initializes and defines program variables, such as plate separation, characteristic impedance, and electrical length for each of the two cells. Program defaults and ADC calibration settings are displayed on the screen at the end of initialization.

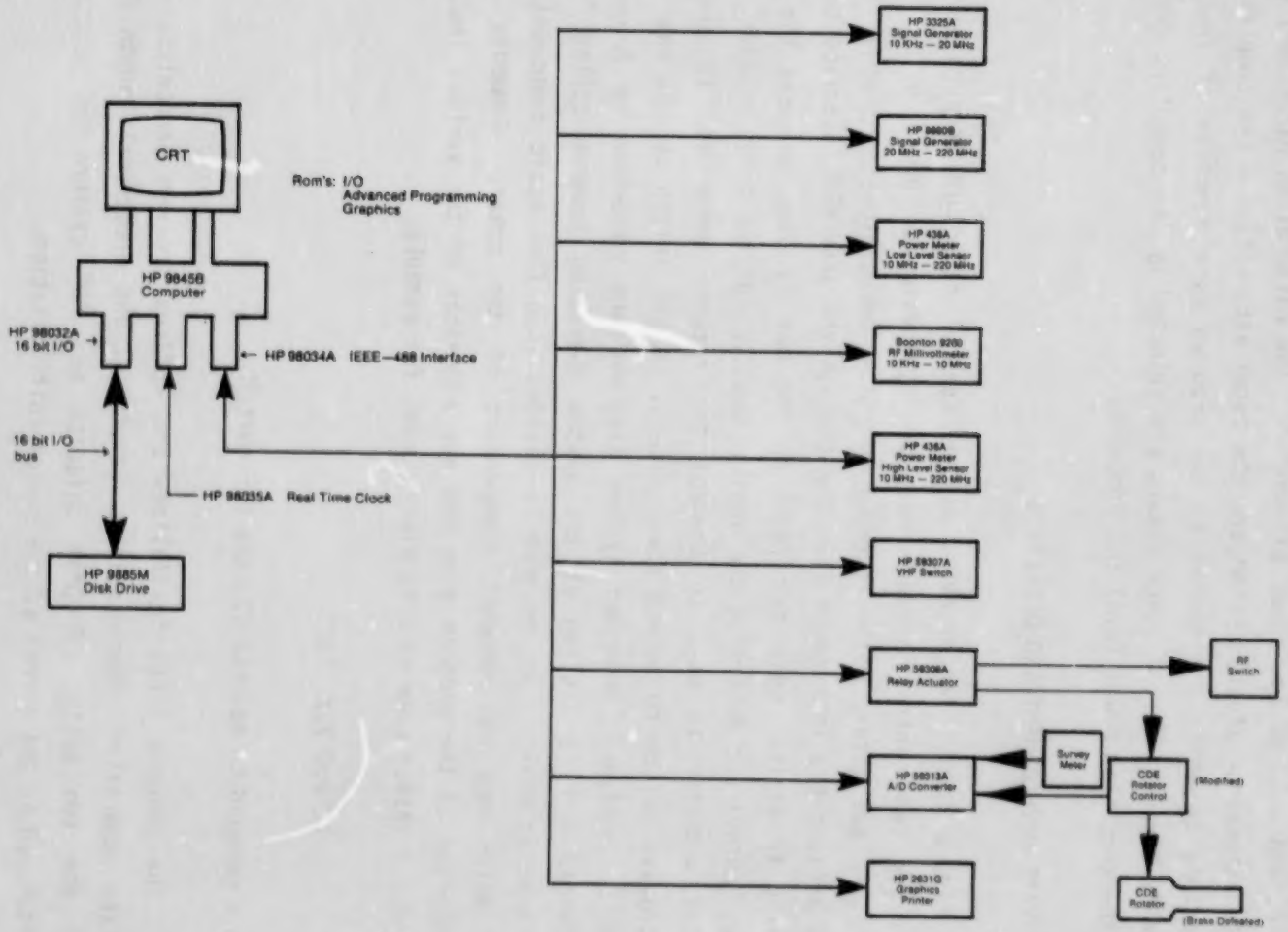


Figure 2. System computer control structure.

The program then will check the status of certain peripherials to guarantee that they are operating and are on-line. It is at this point the operator is allowed to interact with the computer in order to define the measurement. As can be seen from the program listing in Appendix B, the operator must first identify himself, and then identify the equipment involved in the measurement. The field characteristics may then be described by specifying 'electric' or 'magnetic' as valid selections, and the units used to enter the desired field.

The power meter and synthesizer are selected by the computer by means of the bus relay actuator and bus VHF switch, depending on the specified power level and frequency. After calculating the desired setting the computer reads the power meter and can adjust the generator power output until the power meter reads within ±0.1 dB of to the calculated setting corresponding to the desired field strength in the cell. Once the field is established the hazard meter probe is automatically rotated and the hazard meter recorder output is read by an ADC and compared to the known field strength to present a plot of dB error versus rotation angle at each frequency. A manual check of the meter display is made to insure that the recorder output is operating properly.

After the last frequency is completed a summary table and graph of rotation statistics is presented which includes frequency, average reading, average error, high and low error, and error range. These plots show the hazard meter errors as if the field absolute uncertainty is 0dB. Typical plots are given in a later section on testing and sample applications, and in Appendix D.

SECTION 4

BASIC FIELD STRENGTH EXPRESSIONS AND MODAL CHARACTERISTICS OF TEM CELLS

TEM FIELDS AT THE TEST POINT IN A TEM CELL WITH REFLECTIONS

This section describes derivations of expressions for the electric and magnetic fields at the test point within a TEM cell when the load on the cell output is not perfectly matched to the cell's characteristic impedance. The "test point" is defined throughout this report as the point halfway between the cell sidewalls, input and output connectors, and halfway between either the upper or lower cell wall and the septum. High power loads or attenuators generally have fairly large variations in impedance as a function of frequency (typically resulting in voltage standing-wave ratio (VSWR's) as high as 1.1) and can cause standing wave errors (typically up to ±0.4 dB) if the following expression [3] for the electric field with a perfectly matched load is used.

$$E = \frac{\sqrt{P_n R_o}}{b} \quad \text{(V/m) where} \qquad (1)$$

E is the electric field at the test point in volts per meter (V/m), P_n is the net forward or transmitted power through the cell in watts, R_o is the real part of the cell characteristic impedance in ohms, and b is the distance in meters between the septum and the upper or lower cell wall.

The approach described in this report for determining the fields assumes the TEM cell is: (a) driven by a RF power source, (b) is being operated in the TEM mode only, (c) is used for the calibration of essentially non-perturbing field probes, and (d) is terminated in an impedance matched 50 ohm (Ω) absorptive load. Under these conditions the net forward power may be obtained either by (a) a measurement of the forward and reflected power sensed at the cell input or (b) a measurement of the power delivered to a power sensor through an attenuator connected to the output of the TEM cell. In practice we use the latter technique because of its simplicity. The shorted or open cell

is addressed in a later section. An alternative method of determining the field existing within the TEM cell involves a measurement of the RF voltage at the input terminal of the cell. Although this method is not discussed in this report, it is also subject to many of the same considerations of cell mismatch for assigning uncertainty to the resulting electric field within the cell.

Because of reflection, the TEM condition is not met for the standing wave at the test point, and the electric and magnetic fields no longer maintain the free space magnitude ratio of 377Ω [4]. If the magnetic field (H) can be expressed as a function of current and the electric field (E) as a function of voltage at the test point, all that is required is solving the transmission line problem for the current (I) and the voltage (V) at the test point. This is illustrated in the following example for an air filled circular coaxial transmission line.

Example Problem for an Air Filled Circular Coaxial Transmission Line

This example shows how an alternative definition of characteristic impedence can be used to obtain the same impedence formula as the conventional definition for the well known case of air circular coax. The conventional definition is

$$Z_0 = \sqrt{\frac{L}{C}}$$

for a lossless line where L and C are the distributed inductance and capacitance per unit length, respectively [5].

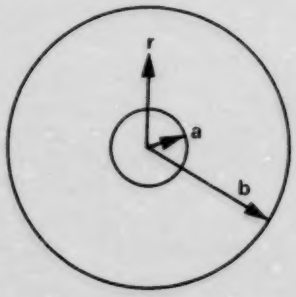


Figure 3. Configuration of a circular air coax.

For a lossless air coax, shown in Figure 3, the field magnitudes are given by magnetostatics and electrostatics [6] to be

$$H = \frac{I}{2\pi r} \quad \text{and} \quad E = \frac{V}{r \ln(b/a)} \tag{2}$$

at any point along the transmission line. The quantities a, b, and r are defined in Figure 3. Both fields are inversely proportional to the radius (r). If Z_0 is defined as the ratio of V/I, such that $E/H = 377\,\Omega = Z_{w_{fs}}$, where $Z_{w_{fs}}$ is the impedance of a plane wave in free space. ($Z_{w_{fs}}$ is pure real, since the electric and magnetic fields are in phase for such a wave) then for an air filled circular coaxial line,

$$\frac{E}{H} = \frac{V}{I} \frac{2\pi}{\ln(b/a)} = 377\,\Omega, \text{ so} \tag{3}$$

$$\frac{V}{I} = \frac{377}{2\pi} \ln(b/a) = Z_0 \tag{4}$$

which is the standard equation for air coax characteristic impedance. This result can also be obtained from the conventional definition. Z_0 is real and a function of geometry only. This alternative definition is used in the next section.

E as a function of V, and H as a function of I for TEM cells

For a TEM cell, consider the following equations for H as a function of I and E as a function of V at the test point. The cross sectional geometry of the rectangular section of the cell is shown in Figure 4, which defines a, b, and g.

$$H \equiv \frac{I}{\left[4b \frac{a}{b} - \frac{2}{\pi} \ln(\sinh \frac{\pi g}{2b})\right]} \tag{5}$$

$$E = \frac{V}{b} \tag{6}$$

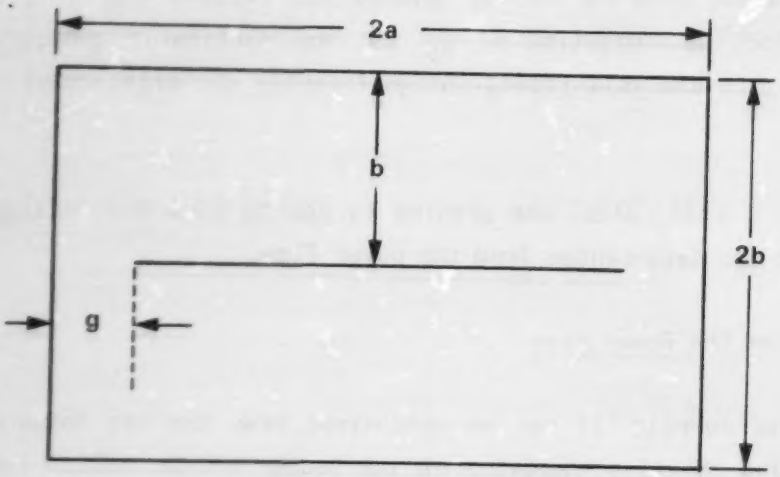


Figure 4. Cross-sectional geometry of a TEM cell.

To determine the characteristic impedance of the cell, set E/H = 377 Ω when $V/I = Z_o$:

$$\frac{E}{H} \cong \underbrace{\frac{V}{b} \cdot 4b \left[\frac{a}{b} - \frac{2}{\pi} \ln\left(\sinh \frac{\pi g}{2b}\right)\right]}_{I} = 377\,\Omega, \tag{7}$$

and

$$Z_o = \frac{V}{I} \cong \frac{377\,\Omega}{4\left[\frac{a}{b} - \frac{2}{\pi} \ln\left(\sinh \frac{\pi g}{2b}\right)\right]} \tag{8}$$

This is the approximate expression given by Crawford without a typically negligible correction for the inter-edge effect which is only significant for a narrow center conductor [7, 8]. Eq. (5) was actually derived from Eq. (8), however, this order of presentation seems more logical since Eq. (5) could have been derived from magnetostatics. A convenient expression obtained from Eqs. (5) and (8) is:

$$H \cong \frac{IZ_o}{377b} \text{ (A/m)}, \tag{9}$$

where Z_0 may be determined from Eq. (8) by geometrical measurements of the cell. Exact theoretical determination of Z_0 for the particular geometry of the cells used in this analysis yields insignificantly different results [9].

Since $E = V/b$ and $H \cong IZ_0/377b$, the problem is now to find the voltage (V) and current (I) at the cell center from the power flow.

Voltage and Current from the Power Flow

The voltage (V) and current (I) can be determined from the net forward or transmitted power and the line impedance at the center of the cell. The complex line impedance (Z_i) can be found from the complex load impedance (Z_l), the cell characteristic impedance (Z_0), half the cell electrical length ($l_e/2$), and the frequency (f). This analysis assumes that the transmission line impedance of the cell (Z_0) is constant along the length of the cell, which is not strictly true; however, the technique does yield an approximate solution. The variation in Z_0 is treated in a later section on error analysis.

Z_l must be measured as a function of frequency. Once Z_l, Z_0, $l_e/2$, and f are known, Z_i can be determined by the common lossless transmission line formula [10].

$$Z_i = Z_0 \left[\frac{Z_l \cos(\beta \frac{l_e}{2}) + jZ_0 \sin(\beta \frac{l_e}{2})}{Z_0 \cos(\beta \frac{l_e}{2}) + jZ_l \sin(\beta \frac{l_e}{2})} \right] \tag{10}$$

where the phase constant $\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$ radians.

Since the net radiofrequency power flowing through the midpoint of the cell is the same as the net power measured at the output, assuming no internal losses,

$$P_n = VI \frac{R_i}{|Z_i|} \tag{11}$$

where $|Z_i| = \sqrt{R_i^2 + X_i^2}$ and $\frac{R_i}{|Z_i|}$ is interpreted as the power factor [11].

Also
$$V = |Z_i| I, \tag{12}$$

where V and I are root-mean-square (rms) values and only the magnitudes are used.

$$P_n = I^2 R_i, \text{ from which } I = \sqrt{\frac{P_n}{R_i}} \quad \text{and}$$

$$V = |Z_i| \sqrt{\frac{P_n}{R_i}} \tag{13}$$

Electric and Magnetic Fields from the Power Flow

Combining equation 6, 9, and 13 yields:

$$E = \frac{V}{b} = \frac{|Z_i| \sqrt{\frac{P_n}{R_i}}}{b} \quad \text{and} \quad H \cong \frac{IZ_o}{377b} = \sqrt{\frac{P_n}{R_i}} \frac{Z_o}{377b} \tag{14}$$

The electric field in Eq. 14 may also be written as:

$$E = \frac{\sqrt{P_n / G_i}}{b} \quad \text{since} \quad G_i = \frac{R_i}{R_i^2 + X_i^2}$$

where G_i is the real part of the line admittance.

The inverse expressions are used to determine the value of power in watts needed to obtain a given field strength; they are

$$P_n = \frac{E^2 R_i b^2}{|Z_i|^2} \quad \text{and} \quad P_n = \frac{H^2 R_i \, 377^2 b^2}{Z_o^2} \tag{15}$$

Note that when there <u>is</u> a perfect match $Z_1 = Z_o$, and Z_o is pure real ($Z_o = R_o$). Eq. (14) then reduces to Eq. (1) for the electric field and magnetic field can be found using the free space ratio:

$$E = \frac{\sqrt{P_n Z_o}}{b} \qquad \text{and } H = \frac{E}{377\Omega}. \tag{16}$$

Also, $P_n = P_m \cdot A$, neglecting mismatch loss (<0.01 dB), where P_m is the power meter reading in watts and A is the attenuation factor, which must be measured as a function of frequency. If the attenuation is 43 dB, A ≡ 20000.

Note that the complex wave impedance Z_w is given by

$$Z_w = Z_i \left(\frac{377\Omega}{Z_o}\right) \text{ where } Z_o \text{ is the real characteristic impedance.} \tag{17}$$

It is useful to see the magnitude of the maximum standing wave error as a function of various reflection parameters for relatively well matched loads, (see Figure 5). Even though reflected power may be small the standing wave error can be significant. Thus the error (mismatch loss) due to not compensating for reflected power can be negligible while the standing wave error is large. For example with a VSWR of 1.1, the mismatch loss is only 0.01dB. This might lead one to believe that the standing wave error is small, however, it is ±0.4dB.

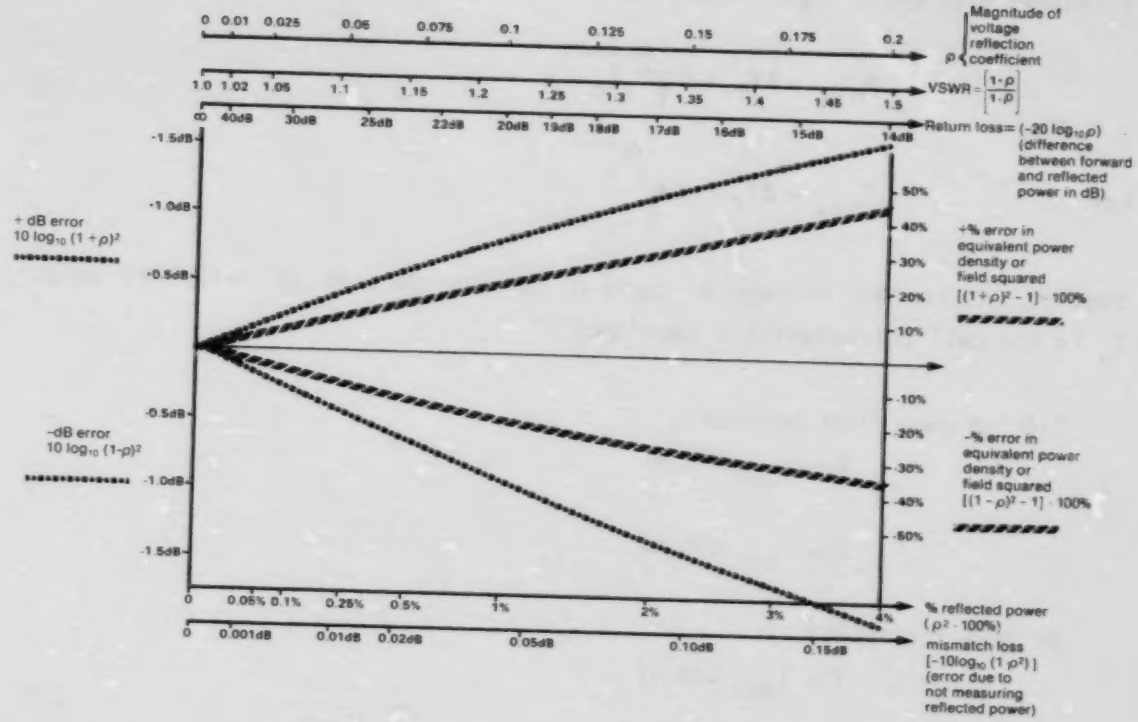

Magnitude of voltage reflection coefficient
VSWR
Return loss= (-20 log10ρ) (difference between forward and reflected power in dB)
+ dB error
10 log10 (1 + ρ)²
+% error in equivalent power density or field squared
[(1 + ρ)² - 1] · 100%
-dB error
10 log10 (1-ρ)²
-% error in equivalent power density or field squared
[(1 - ρ)² - 1] · 100%
% reflected power
(ρ² · 100%)
mismatch loss
[-10log10 (1 ρ²)]
(error due to not measuring reflected power)

Figure 5. Standing wave error as a function of reflection parameters.

The Shorted or Open Cell

In the case where a cell is terminated with a short or open circuit the previous analysis cannot be applied, since the forward and reflected power are equal and the net power P_n is zero. Also, at certain frequencies, the line impedance is infinite. Thus, another objective of this analysis is to determine the absolute electric and magnetic field strengths at the test point when the load end of the cell is either open or short circuited.

In this case, the forward power (P_f) is equal to the reflected power (P_r) for a lossless cell and either one may be measured with a directional coupler at the cell input. The coupler should have the same impedance as the cell characteristic impedance.

For total reflection, the maximums in the voltage and current for the standing-waves which repeat every half-wavelength, are:

$$V_{max} = 2V_f = 2\sqrt{P_f Z_o} \tag{18}$$

and

$$I_{max} = 2I_f = 2\sqrt{\frac{P_f}{Z_o}}$$

that is, twice the voltage or current for the forward or reflected wave. Z_o is the cell characteristic impedance.

Backing away from the short:

$$V = V_{max} |\sin \theta| \tag{19}$$

$$I = I_{max} |\cos \theta|$$

Or from the open:

$$V = V_{max} |\cos \theta| \tag{20}$$

$$I = I_{max} |\sin \theta|$$

where θ is the electrical angle back to the cell center; for a cell with electrical length l_e,

$$\theta = \frac{\pi f l_e}{c} \tag{21}$$

where we have moved back toward the generator $l_e/2$ to the center of the cell and f is the frequency (MHz) and c the speed of light is 300 MHz·m (equivalent to 3×10^8 m/sec) [12].

Combining equations 18 through 21 with

$$E = V/b \quad \text{and} \quad H = \frac{IZ_o}{377\ b} \tag{22}$$

where b is the plate separation, gives:

$$E = \frac{2\sqrt{P_f Z_o}\left|\sin\left(\frac{\pi f l_e}{c}\right)\right|}{b}$$

$$H = \frac{2\sqrt{P_f Z_o}\left|\cos\left(\frac{\pi f l_e}{c}\right)\right|}{377\, b}$$

Short (23)

$$E = \frac{2\sqrt{P_f Z_o}\left|\cos\left(\frac{\pi f l_e}{c}\right)\right|}{b}$$

$$H = \frac{2\sqrt{P_f Z_o}\left|\sin\left(\frac{\pi f l_e}{c}\right)\right|}{377\, b}$$

Open (24)

The wave impedance, which is always pure imaginary such that E and H are 90° out of time phase, is given by:

$$Z_w = j377\tan\left(\frac{\pi f l_e}{c}\right) \quad \text{Short} \quad (25)$$

$$Z_w = \frac{j377}{\tan\left(\frac{\pi f l_e}{c}\right)} \quad \text{Open} \quad (26)$$

Both of these expressions approach infinity at nulls in H.

From Eqs. 23 and 24 the squares of the electric and magnetic fields are given as:

$$E^2 = \frac{4P_f Z_o \sin^2\left(\frac{\pi f l_e}{c}\right)}{b^2} \quad \text{and} \quad H^2 = \frac{4P_f Z_o \cos^2\left(\frac{\pi f l_e}{c}\right)}{377^2 b^2} \quad \text{Short} \quad (27)$$

$$E^2 = \frac{4P_f Z_o \cos^2\left(\frac{\pi f l_e}{c}\right)}{b^2} \quad H^2 = \frac{4P_f Z_o \sin^2\left(\frac{\pi f l_e}{c}\right)}{377^2 b^2} \quad \text{Open} \quad (28)$$

Eqs. 27 and 28 are plotted in Figures 6, 7, 8, and 9 as a function of frequency, with the power normalized to P_f = 1 watt for two specific TEM cells used for instrument calibrations in the EPA laboratory. These cells are the Instruments for Industry (IFI) models CC-105 and CC-101.5.

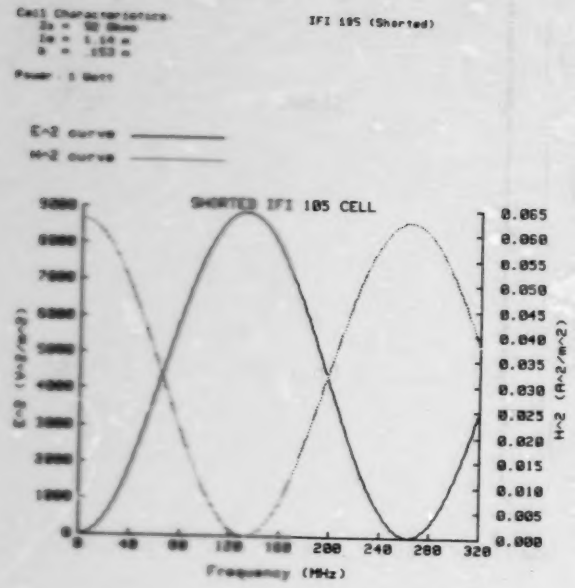


Figure 6. Squares of electric and magnetic field for a shorted CC-105 cell

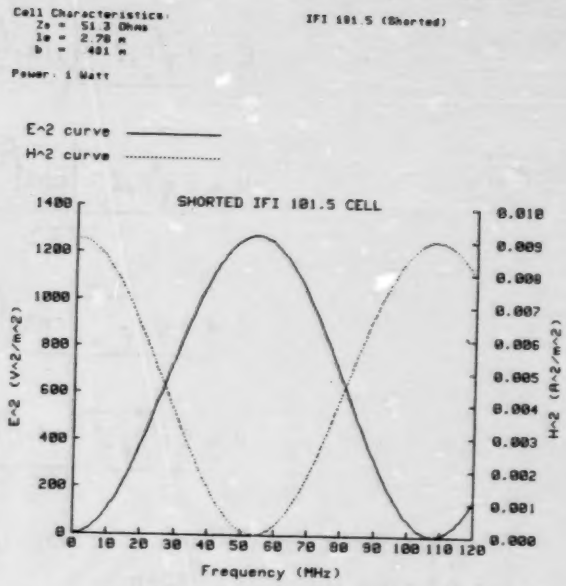


Figure 7. Squares of electric and magnetic field for a shorted CC-101.5 cell

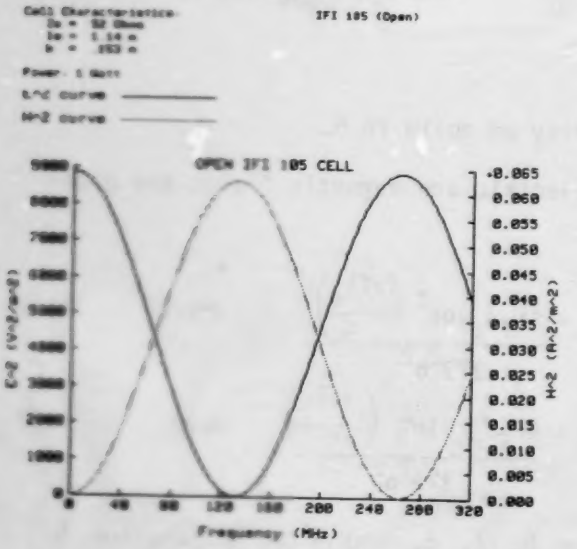


Figure 8. Squares of electric and magnetic field for an open CC-105 cell

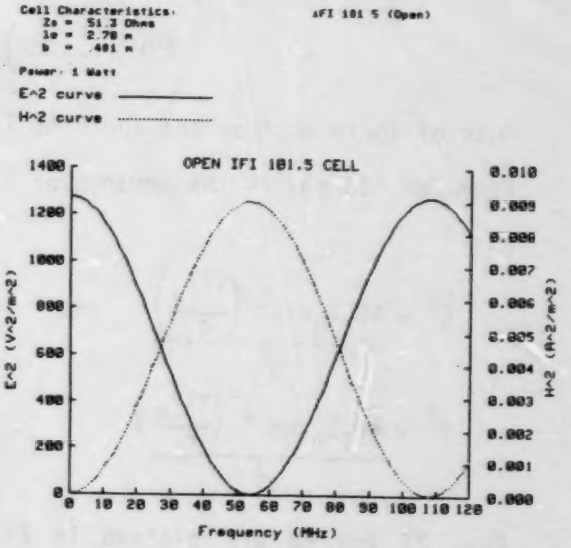


Figure 9. Squares of electric and magnetic field for an open CC-101.5 cell

This type of field set-up with TEM cells is useful when evaluating, for example, the electric field response of magnetic field sensors or the magnetic field response of electric field sensors.

TEM FIELDS THROUGHOUT THE TEM CELL CROSS SECTION

The two-dimensional electrostatic problem for the electric field distribution of the TEM mode has been solved by Tippet [13]. The present analysis will illustrate these field variations for the particular geometry of the two cells used in the EPA laboratory and extend the analysis to provide explicit expressions for the magnetic field as a function of current at the test point.

Electric Field Distribution of the TEM Mode

The electric field distribution was solved by Tippet [13] using the Schwarz-Christoffel transformation resulting in elliptic integrals and Jacobian elliptic functions in the final result. A program similar to Tippet's was written in BASIC for a desktop computer which determines $E_x(x,y)$ and $E_y(x,y)$ normalized to V/b, which are the components of the transverse E field. The coordinate system is shown in Figure 10. The z-axis (not shown) would come out of the paper with the z-coordinate equal to zero at the cell's longitudinal center. The test point coordinates are $x = 0$, $y = \pm b/2$, and $z = 0$. The fields are symmetric in the four quadrants so calculations are made only in the first quadrant with x and y positive.

The field strength variation over the measurement probe's volume, with the probe center at the test point is relevant to the calibration of survey probes. Calculations of the field magnitude extremes along circles centered on the test point were made and are displayed in Figures 11 and 12 for the two IFI cells. The field strength magnitude is normalized to V/b and given in dB. For example, a spherical field probe with a radius of 5 cm in the smaller IFI 105 cell would have a field variation of ±0.4 dB over its volume. This analysis neglects small field variations in the z-direction due to standing waves.

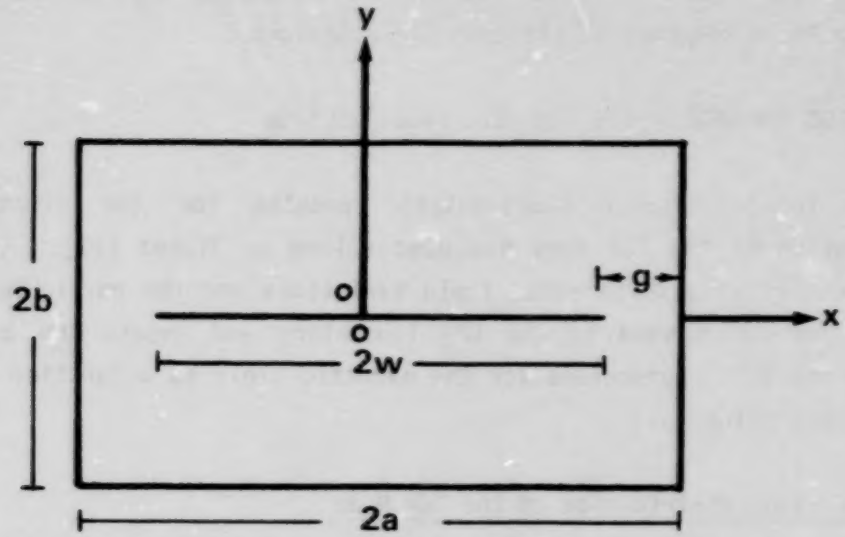


Figure 10. Cross section through the center of a TEM cell with coordinate system shown.

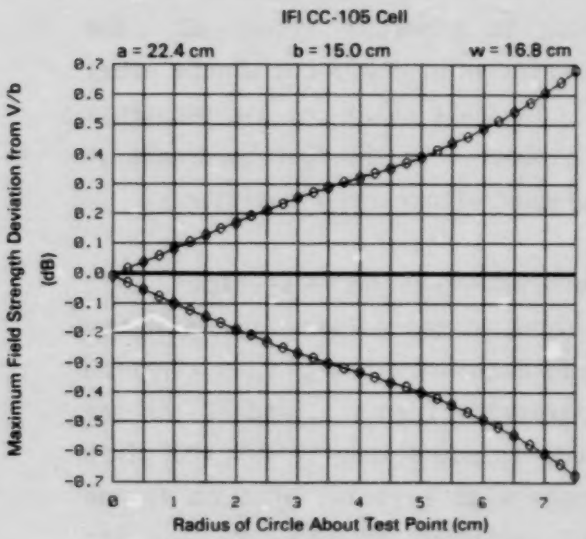


Figure 11. Field magnitude extremes for the CC-105 cell.

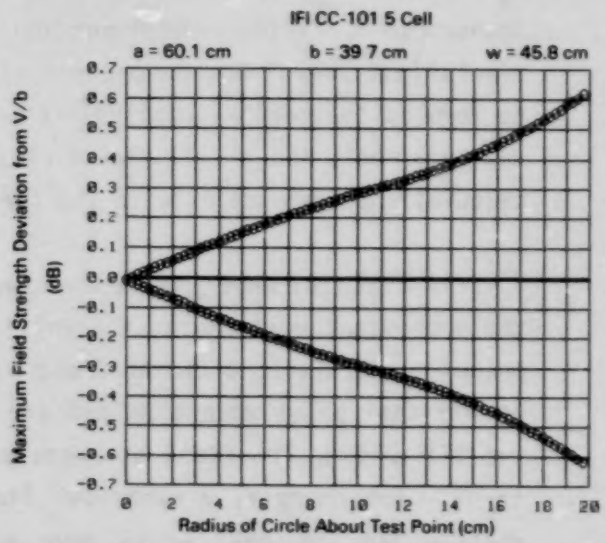


Figure 12. Field magnitude extremes for the CC-101.5 cell.

Perspective views of the normalized magnitude of the field strength within the two TEM cells are given in Figures 13 and 14. Results for only the first quadrant are shown. The field is slightly higher below the test point at the septum (x = 0, y = 0) and is lower above the test point at the shield (x = 0, y = b). The field goes to zero at the corner (x = a, y = b) and goes to infinity at the septum edge (x = w, y = 0) because of the zero thickness septum model used.

Magnetic Field Distribution of the TEM Mode

For either the forward or reflected wave the magnetic field is given by the TEM requirement from the electric field. If the normalized electric field is $\vec{E}(x,y)$, the actual electric field is $\vec{E}(x,y) \cdot \frac{V}{b}$, and the magnetic field without reflections is

$$\vec{H}(x,y) = \pm\overleftrightarrow{Y}\cdot\vec{E}(x,y)\cdot\frac{V}{b} \tag{29}$$

The expression with reflections is

$$\vec{H}(x,y) = \pm\overleftrightarrow{Y}\cdot\vec{E}(x,y)\cdot\frac{Z_o I}{b} \tag{30}$$

where $\overleftrightarrow{Y}$ is the dyadic wave admittance [14]

$$\overleftrightarrow{Y} = Y(\hat{j}\hat{i} - \hat{i}\hat{j}) \text{ and } Y = \sqrt{\frac{\varepsilon_o}{\mu_o}} = \frac{1}{377\Omega}.$$

The above expression illustrates that without reflections the magnetic field is transverse to the electric field and has the magnitude given by the electric field magnitude divided by the impedance of free space. The voltage V and current I are the same as in the previous section on fields at the test point.

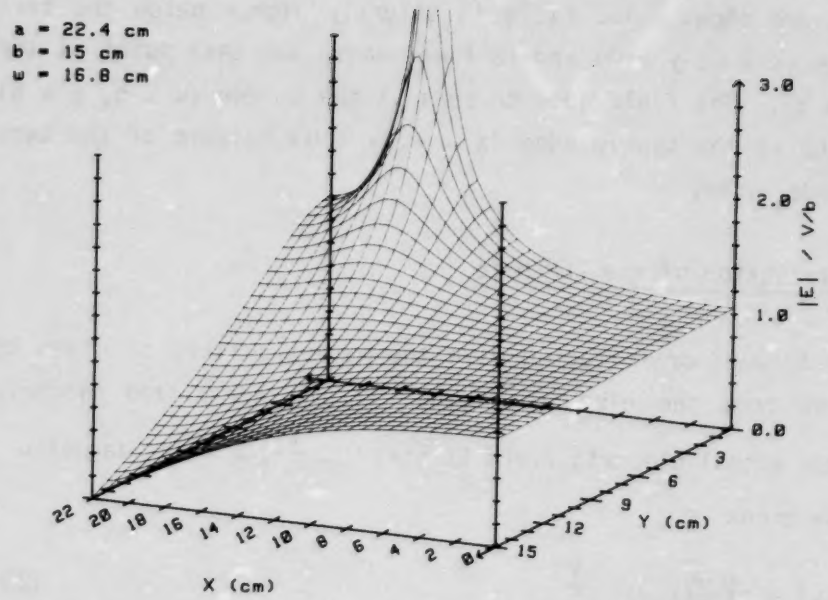


Figure 13. Normalized field strength IFI CC-105 TEM cell.

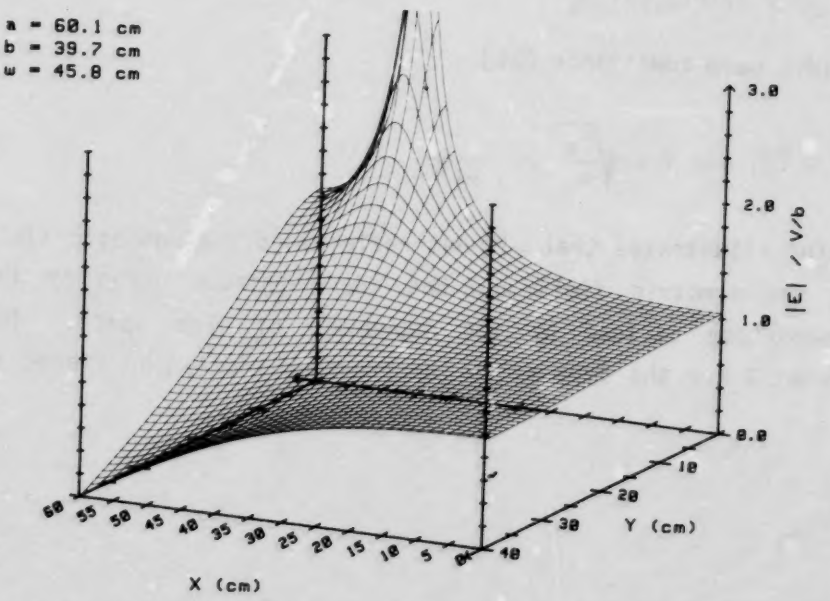


Figure 14. Normalized field strength IFI CC-101.5 TEM cell.

MODAL CHARACTERISTICS OF TEM CELLS

There is some controversy about the modal and resonant characteristics of TEM cells in general and how these characteristics affect the useful upper frequency limit of the cells [15]. There are two general types of boundary value problems which are relevant: (type 1) the two-dimensional uniform waveguide problem in which the waveguide has an indefinite length and (type 2) the three-dimensional resonant cavity problem in which definite resonant frequencies are determined. Tippet and others [16, 17, 18] have solved the shielded rectangular coaxial stripline problem. These analyses are of type 1 since they consider only the cross sectional dimensions of the cell. The type 2 problem applied to the full three-dimensional tapered shield and septum of a TEM cell does not appear to have been solved and is beyond the scope of this report. The uniform waveguide solutions (type 1) imply by their resultant cutoff frequencies that, beyond some frequency, higher modes propagate and the cell cannot be used simply as a TEM transmission line. The resonant cavity view (type 2) suggests that between resonant frequencies the cell will operate normally and can be used to much higher selected frequencies until the resonances begin to overlap. Measurements made of the longitudinal electric and magnetic fields (E_z and H_z) suggest that resonant frequencies predominate starting at 120 MHz in the CC-101.5 cell and 320 MHz in the CC-105 cell. Isolated wide-band fields characteristic of propagating modes are also seen (Figure 22c). Since the cavity problem is unsolved, the best that can be done when comparing theoretical results to experimental return loss and field measurement data, is to use the common expression for the resonant frequency of rectangular waveguides, with flat conductive ends, as a function of cutoff frequency and length. Three lengths between the beginnings, middles, and ends of the tapers were tried as possible effective lengths. The data suggest different effective lengths for different modes.

Hill [19] was able to more positively identify the TE resonances by measuring the y component of the electric field at several points in the cell. He also found different effective lengths for different modes. Here, only the z component of the magnetic field was measured to establish the

existence of a resonance condition. Identifying which resonance condition was present was usually ambiguous.

Cutoff Frequencies

This section addresses the uniform waveguide cutoff frequency solutions for the geometries of the two cells used. The relevant parameters are the cross section dimensions a, b, and w; i. e., the half-width, half-height, and half-septum width for the CC-101.5 larger cell and the CC-105 smaller cell. The TE and TM modes fall into two classes: those perturbed by the existence of the center conductor or septum (n odd), and those unperturbed (n even) which have only vertical or normal electric fields and horizontal or tangential magnetic fields at the septum [20]. Table 1 lists some of the lower order TE and TM modes.

TABLE 1. LOWER ORDER TE_{mn} or TM_{mn} MODES.
Perturbed Modes circled.
TM_{mn} modes are not allowed in the first row or column with m or n = 0.

m \ n	0	1	2	3	...
0		(01)	02	(03)	
1	10	(11)	12	(13)	
2	20	(21)	22	(23)	...
3	30	(31)	32	(33)	
4	40	(41)	42	(43)	
.	.	.			
.	.	.			
.	.	.			

The two lowest perturbed TE modes are TE_{01} and TE_{11}, the two lowest perturbed TM modes are TM_{11} and TM_{21}. A program similar to that in Appendix L of Tippet's dissertation [21] was used to determine the cutoff

frequencies of these perturbed modes. The unperturbed modes are the same as for hollow rectangular waveguide with dimensions 2a x 2b. Their frequencies are determined in MHz from

$$f_{c(mn)} = \frac{300\sqrt{4m^2b^2 + 4n^2a^2}}{8ab} \quad \text{(MHz)} \tag{29}$$

where 300 is the speed of light in vacuum in MHz·m (m x 10^6/sec) units derived from [22]. For the CC-101.5 cell, a = 0.601m, b = 0.397m, w = 0.458m; for the CC-105 cell, a = 0.224m, b = 0.150m, w = 0.168m. Table 2 gives the predicted TE cutoff frequencies and Table 3 gives the predicted TM cutoff frequencies.

TABLE 2. PREDICTED TE CUTOFF FREQUENCIES

CC-105 cell, Unperturbed modes:	TE_{10}	$f_{c(10)}$ =	335 MHz
	TE_{20}	$f_{c(20)}$ =	670 MHz
	TE_{02}	$f_{c(02)}$ =	1000 MHz
Perturbed modes:	TE_{01}	$f_{c(01)}$ =	281 MHz
	TE_{11}	$f_{c(11)}$ =	528 MHz
CC-101.5 cell, Unperturbed modes:	TE_{10}	$f_{c(10)}$ =	125 MHz
	TE_{20}	$f_{c(20)}$ =	250 MHz
	TE_{02}	$f_{c(02)}$ =	378 MHz
Perturbed modes:	TE_{01}	$f_{c(01)}$ =	105 MHz
	TE_{11}	$f_{c(11)}$ =	197 MHz

TABLE 3. PREDICTED TM CUTOFF FREQUENCIES

CC-105 cell, Unperturbed modes:	TM_{12}	$f_{c(12)} = 1055$ MHz
	TM_{22}	$f_{c(22)} = 1204$ MHz
	TM_{32}	$f_{c(32)} = 1417$ MHz
Perturbed modes:	TM_{11}	$f_{c(11)} = 1052$ MHz
	TM_{21}	$f_{c(21)} = 1194$ MHz
CC-101.5 cell, Unperturbed modes:	TM_{12}	$f_{c(12)} = 398$ MHz
	TM_{22}	$f_{c(22)} = 453$ MHz
	TM_{32}	$f_{c(32)} = 532$ MHz
Perturbed modes:	TM_{11}	$f_{c(11)} = 397$ MHz
	TM_{21}	$f_{c(21)} = 450$ MHz

Only those perturbed modes for which Tippet's program was developed have been calculated; higher order perturbed modes may have cutoff frequencies less than the higher cutoff frequencies for unperturbed modes given. The accuracy of these cutoff frequencies is determined by the accuracy of the cell demensions or ± 1%.

Resonant Frequencies

The equation for the resonant frequencies of hollow rectangular waveguide, turned into a resonant cavity by putting flat conductors on each end [23], is:

$$f_{res} = \sqrt{f_c^2 + \frac{cp^2}{2d}} \quad \text{(MHz)} \tag{30}$$

giving a series of resonances for each cutoff frequency. c = 300 MHz·m, d = resonant length (m), and p = 1, 2, 3... for TE modes or p = 0, 1, 2 ...

for TM modes. Since d is not well-defined for the cell with tapers, three values of d are used: d_1, d_2, and d_3 as defined in Figure 15.

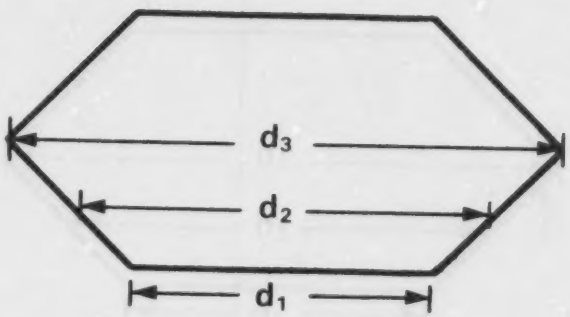


Figure 15. Effective lengths defined.

The percentage of taper used in the effective lengths d_1, d_2, and d_3 are 0%, 50%, and 100% respectively. The cutoff frequencies, range of resonant frequencies using 0% to 100% of the tapers, and observed resonant frequencies found in the next section are shown in Figures 14, 15, 16, and 17. The resonant frequency ranges were calculated for p = 1, 2, and 3 for TE modes, and p = 0, 1, 2, 3 for TM modes. The horizontal "error bars" represent the range of resonant frequencies with the left end using 100%, the circle 50%, and the right end using 0% of the tapers. The short vertical bars give the cutoff frequencies and the vertical lines extending from the bottom to top show the resonant frequencies which were observed. If an observed resonance frequency crosses more than one range of resonance frequencies the identification is ambiguous. Hill [19] found for a cell having 2b = 0.6m that ~50% of the tapers, for TE_{10} and TE_{11} resonances, and ~81% of the tapers, for TE_{01} resonances, should be included in the effective length.

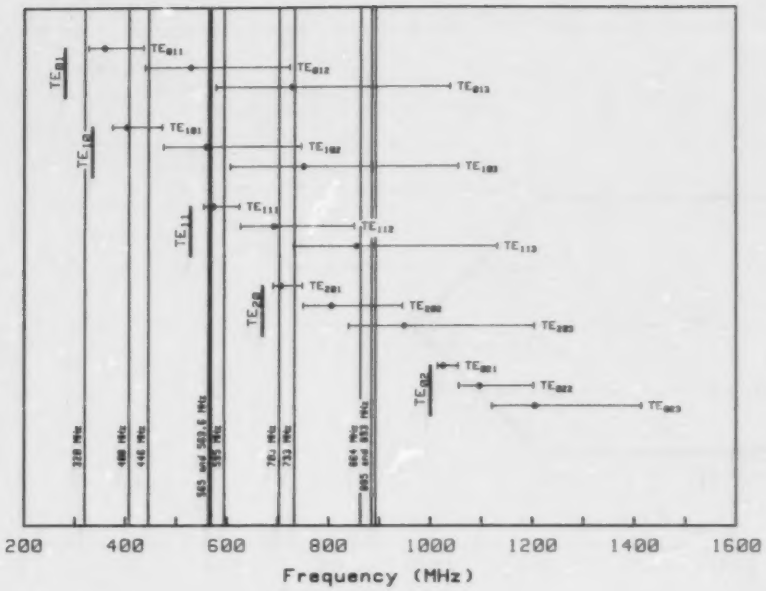


Figure 16. CC-105 cell TE cutoff frequencies, range of resonant frequencies, and observed resonant frequencies.

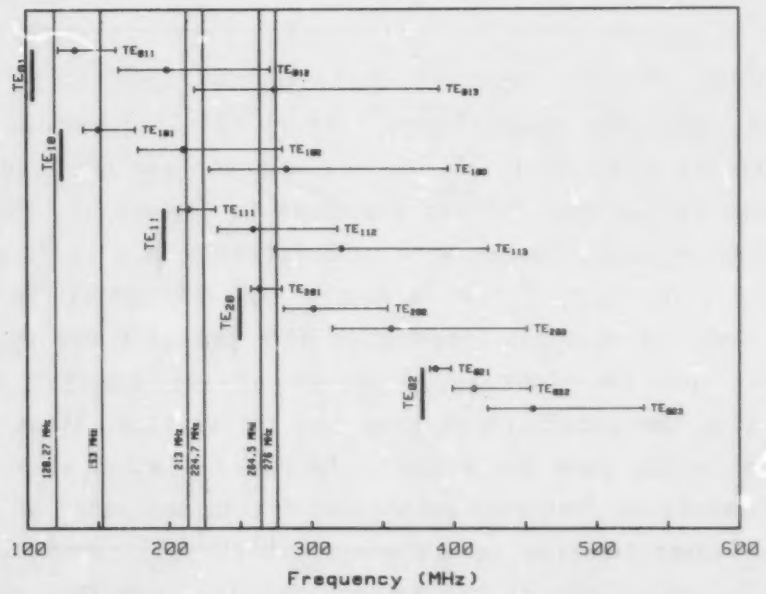


Figure 17. CC-101.5 cell TE cutoff frequencies, range of resonant frequencies, and observed resonant frequencies.

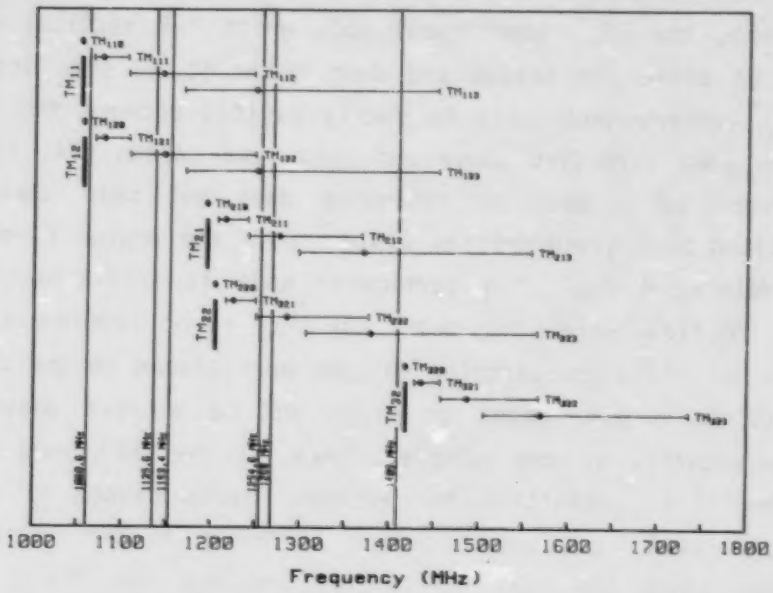


Figure 18. CC-105 cell TM cutoff frequencies, range of resonant frequencies, and observed resonant frequencies.

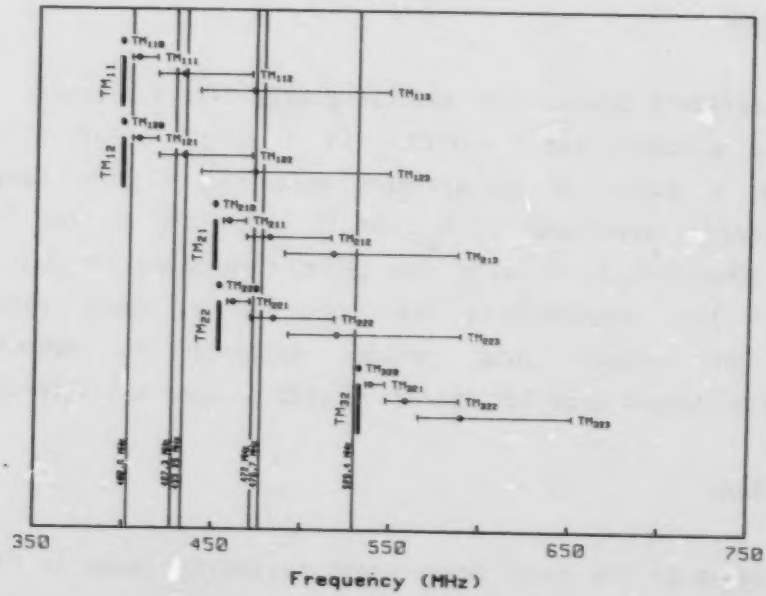


Figure 19. CC-101.5 cell TM cutoff frequencies, range of resonant frequencies, and observed resonant frequencies

The modes and associated resonances which have field distributions similar to the TEM field will be strongly excited by driving the cell with coax; for example, the TE_{11} (perturbed) mode which has vertical electric fields pointed up above the septum and down below it at some instant in time. The TE_{10} (unperturbed) mode is poorly excited because the electric field is in the same direction above and below the septum [24, 25]. The possible existence of a mode or resonance does not mean that it is necessarily excited by a given driving field. Here the septum is driven to create a TEM driving field; if a particular mode is anti-symmetric with respect to the TEM field some nonsymmetry may have to be introduced for the mode to be excited. If a transmitting antenna were placed in the cell with the septum passive, a mode might or might not be excited depending on location and orientation of the antenna. Thus, if the cell were used for emission testing (i.e., detecting the emitted fields caused by a device inserted in the cell), one would expect different higher modes to be strongly excited since the coax TEM fields are not the fields causing excitation. Emission testing or "radiated emanations measurements" are discussed by Crawford [26].

Modal Measurements

Using a measurement system that simultaneously displays return loss and the magnetic or electric field detected by a single polarization field detection probe, a number of measurements were made of the longitudinal fields. Measurements were made of H_z for TE modes and E_z for TM modes, principally at the test point with the cells terminated in 50 Ω. (When swept insertion loss measurements were compared to swept return loss measurements, the return loss method appeared to detect modal characteristics different from TEM operation with greater sensitivity.)

Measurement System

A block diagram of the modal measurement system is shown in Figure 20. The spectrum analyzer, tracking generator, and directional coupler form a swept return loss measurement and display system. On the spectrum analyzer 0dB return loss is at the top reference line; 20 dB return loss, for example, would be two divisions below the reference line. Return loss is

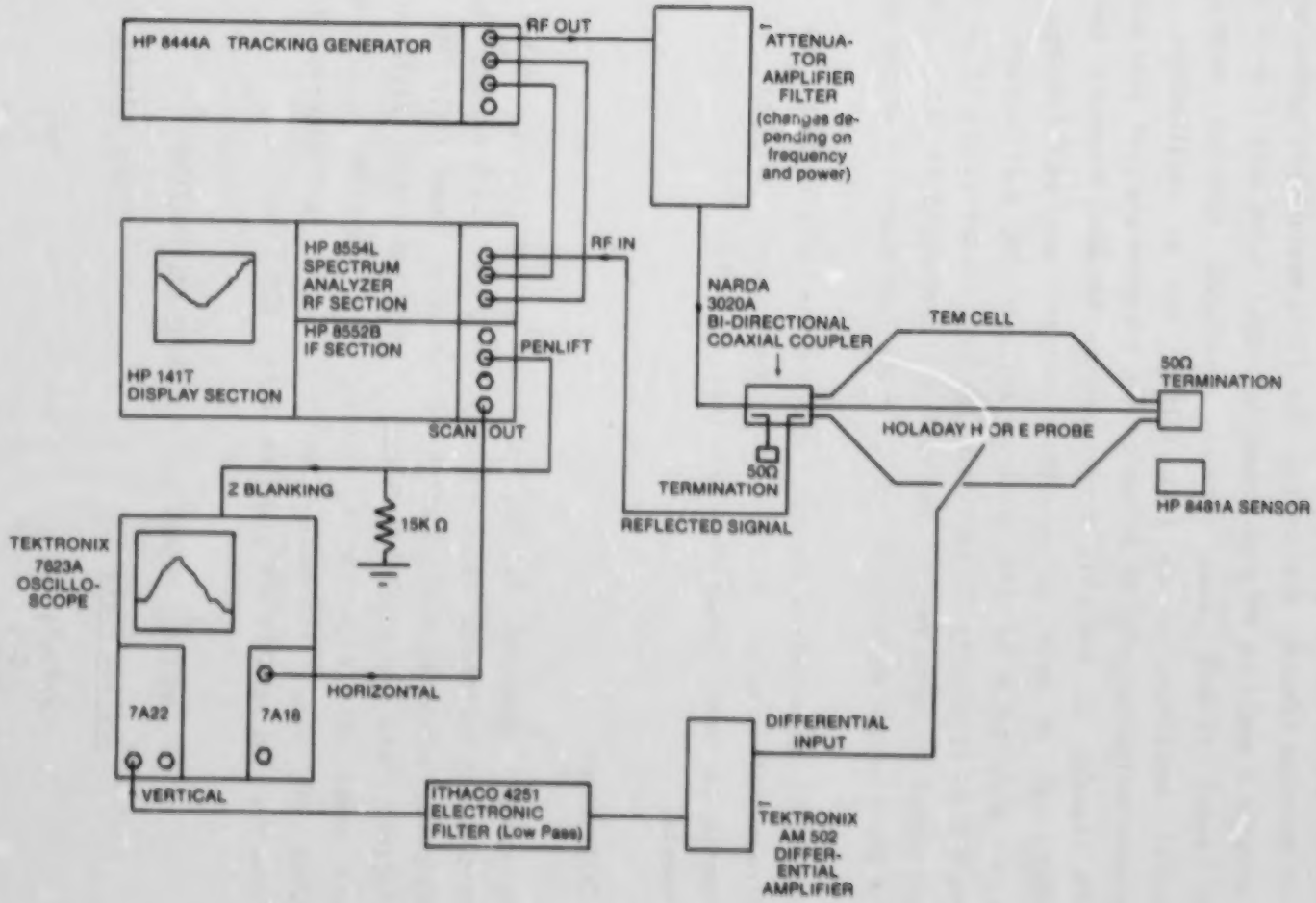


Figure 20. Modal measurement system block diagram.

defined as $-20 \log_{10}\rho$, where ρ is the magnitude of the voltage reflection coefficient. Different amplifiers and filters, depending on frequency, are used between the tracking generator and directional coupler to increase power and decrease harmonic distortion. The field measurement system used a single axis of a modified Holaday production model three axis E or H probe (Holaday model HI-3001 used without associated read-out meter), a differential amplifier, a low pass filter, and an oscilloscope. The oscilloscope horizontal axis is driven by the spectrum analyzer scan out and pen lift signals, so there is correspondence between frequency and the horizontal axis of both the spectrum analyzer and oscilloscope. CRT photographs were taken of the spectrum analyzer and oscilloscope. Scan rates were slow (typically 10 sec) with low pass filter values of 10 Hz to increase signal to noise ratio. The cell was terminated in 50 Ω; alternatively a power sensor was used to determine absolute power out of the cell.

Return loss measurements are not corrected for variations in coupling of the directional coupler within each measurement, so that wideband measurements at lower frequencies are less accurate than the narrow band measurements.

Probe Calibration

The probe connected to the differential amplifier, filter, and oscilloscope was calibrated at 50 MHz only, in the CC-101.5 cell operated in the standard, automated configuration to establish known field strengths. The electric field probe axis is lined up with the TEM E_y field and the magnetic probe axis with the H_x field. The probe dc output voltage corrected for the differential amplifier gain is measured on the oscilloscope. The results are given in Table 4 and 5.

TABLE 4. MAGNETIC FIELD PROBE CALIBRATION

Applied Field	Probe Voltage
(A^2/m^2)	(mV)
0.001	0.2
0.01	2.0
0.1	14
1	62

TABLE 5. ELECTRIC FIELD PROBE CALIBRATION

Applied Field	Probe Voltage
(V^2/m^2)	(mV)
0.1	0.02
0.5	0.1
1.0	0.2
10	1.9
100	15.2
500	52
1000	82
10,000	340

Up to 0.01 A^2/m^2 and 10 V^2/m^2 the probes, when operating into the 1 M Ω input impedance of the differential amplifier, have a square law response. The same calibration is used at all frequencies. This calibration combined with the power measurement allows an approximate comparison between the expected TEM fields (H_x and E_y) and the measured resonant fields (H_z and E_z).

Results

To detect the resonances associated with the TE modes, the H_z component of the field was measured. Figure 21 shows the results for the H_z measurements in the large CC-101.5 TEM cell. The location in the cell in (x,y,z) coordinates is given. The vertical scale is given in μV/div at the input to the differential amplifier. The horizontal axis is frequency, either start and stop frequency or center frequency and span per division are given for both return loss and field plots. For up to 2000μV the conversion factor for magnetic field is $5\mu A^2/m^2/\mu V$ see Table 4. From the measured power the expected TEM field strengths are calculated from the matched cell expressions at the test point:

$$E_y^2 = \frac{PZ_o}{b^2} \qquad H_x^2 = \frac{E_y^2}{377^2} \tag{31}$$

Using $Z_o = 52.0\Omega$ and b = 0.153 m for the CC-105 and $Z_o = 51.3\Omega$ and b = 0.401 m for the CC-101.5 results in the following expressions in convenient units.

CC - 105	CC - 101.5
$E_y^2 \left(\frac{V^2}{m^2}\right) = 2.22 \cdot P(mW)$	$E_y^2 \left(\frac{V^2}{m^2}\right) = 0.319 \cdot P(mW)$
$H_x^2 \left(\frac{\mu A^2}{m^2}\right) = 15.6 \cdot P(mW)$	$H_x^2 \left(\frac{\mu A^2}{m^2}\right) = 2.24 \cdot P(mW)$

(32)

Large changes in H_z were seen as a function of position in the cell, thus some measurements were made away from the test point. The (+w,+b/2,0) measurements were made at the point halfway between the septum and cell side wall, and directly above the septum edge. The CC-101.5 H_z measurements were made between 100 and 300 MHz. Figures 21 a and b give the fields and return loss from 100 to 200 MHz at the septum edge position. The second field peak at 153 MHz was not observed at the test point. Only amplifier noise was seen between the two peaks, implying that the cell is usable between resonances. The return loss values are not corrected for coupler directivity, which was specified to be better than 35 dB. In all cases some change in return loss is seen for each field strength peak. Figures 21 c and d are narrow-band measurements around the peak at 120.27 MHz; the probe was at the test point with the peak H_z field strength 14 dB above the expected TEM H_x value, even though the return loss was 30 dB. Figure 21 e,f,g show two measurement locations from 200 to 300 MHz. Strong return loss peaks are observed with relatively weak fields at the test point, however above the septum edge the field is very strong at 213 MHz. Figure 21 h-m are narrow band examinations of the peaks at 213, 224.7, and 264.5 MHz. Table 6 summarizes the results.

The H_z peaks must be TE resonances. Only the predicted $f_{res\ (011)} = 122.55$ MHz is low enough in frequency to be the measured peak at 120.27 MHz. The peak at 213 MHz is probably the $f_{res\ (111)}$ resonance since it is expected to be strongly excited and has been predicted and measured by Tippet [27] at the National Bureau of Standards. Note that in Figure 21 m the return loss reference at 0 dB is one division lower than normal.

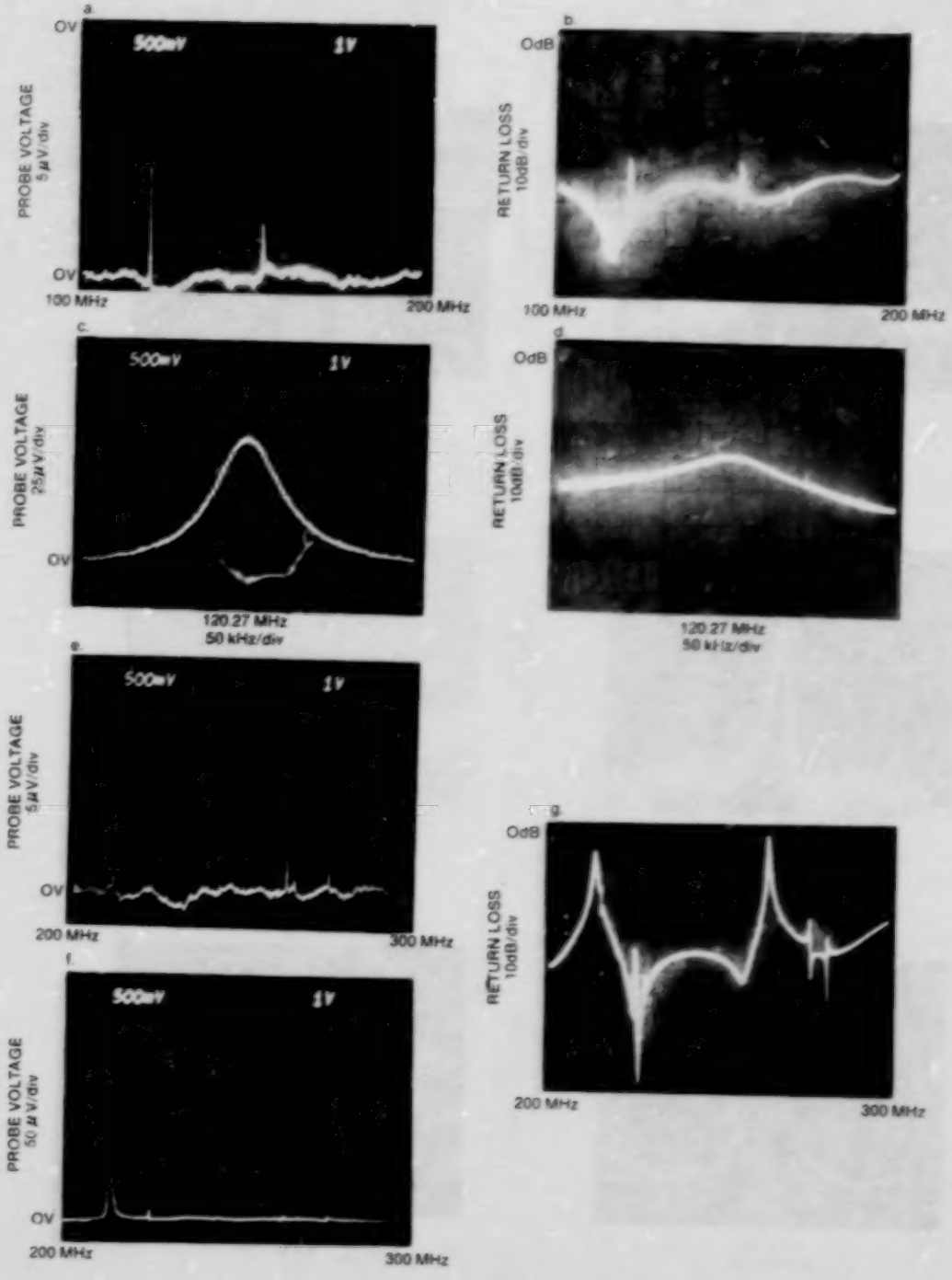


Figure 21(a-g). CC-101.5 cell TE measurements.

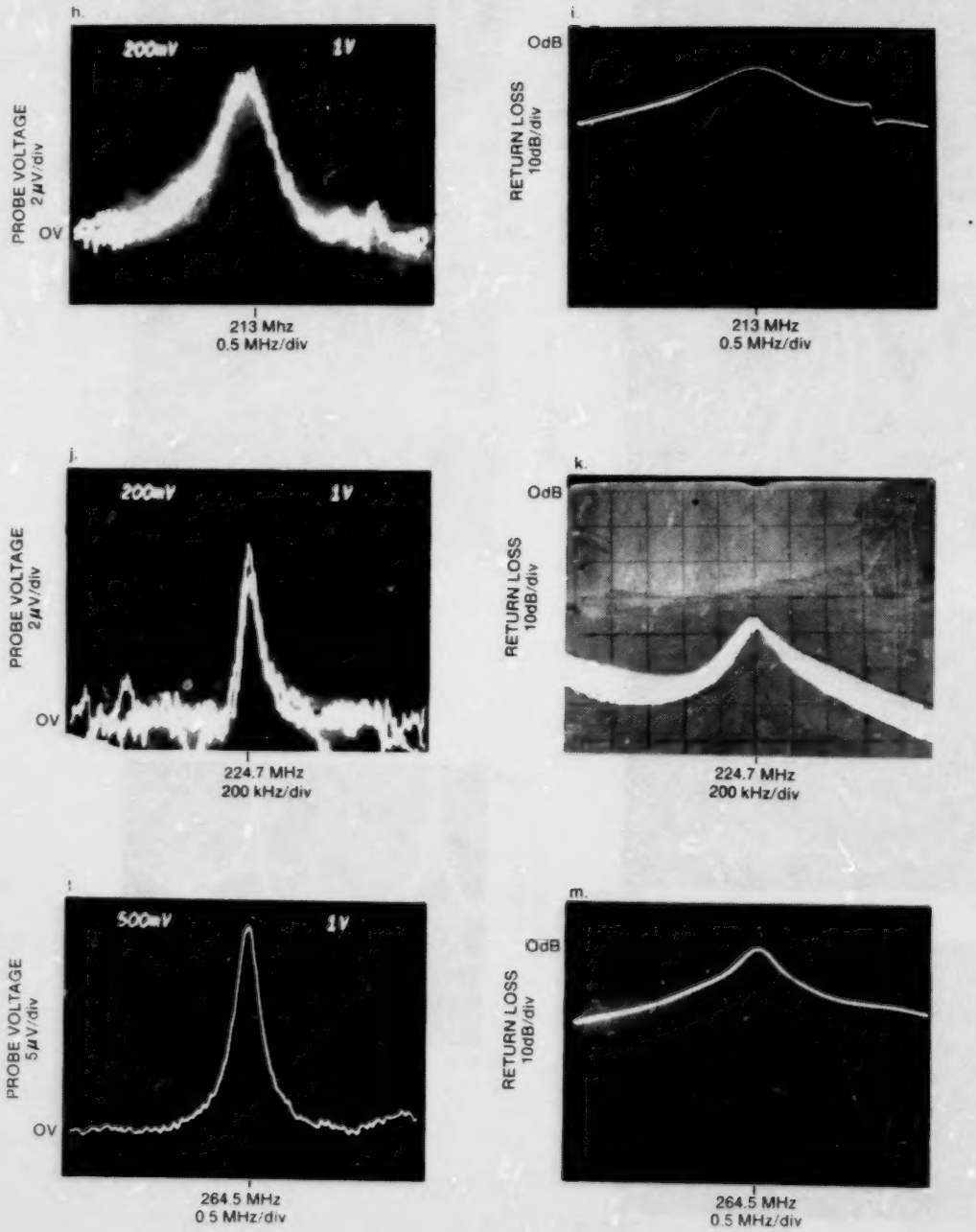


Figure 21(h-m). CC-101.5 cell TE measurements.

TABLE 6. CC - 101.5 CELL TE MEASUREMENTS

See Fig. 21 (letter)	Location (x,y,z)	Power (dBm)	Frequency (MHz)	H_z^2 Peak Field ($\mu A^2/m^2$)	H_x^2 TEM Field ($\mu A^2/m^2$)	Return Loss (dB)
c,d	(0,b/2,0)*	10	120.27	525	22	30
a,d	(w,b/2,0)	7	120	88	11	30
a,b,d	(w,b/2,0)	7	153	37	11	35
e,g	(0,b/2,0)	6	213	15	9	65
e,g	(0,b/2,0)	6	224.7	25	9	33
e,g	(0,b/2,0)	6	264.5	25	9	0
e,g	(0,b/2,0)	6	276	13	9	25
f,g	(w,b/2,0)	6	213	1250	9	5
h,i	(0,b/2,0)	8	213	46	14	8
j,k	(0,b/2,0)	8	224.7	45	14	37
l,m	(0,b/2,d/4)	8	264.5	145	14	0

* test point = (0,b/2,0)

H_z measurements in the smaller CC-105 cell were all made at the test point between 300 and 914 MHz. No resonances were seen below 300 MHz. Both cells were penetrated with the probe through an oblong hole (b/2,b,b/2) with dimensions approximately 3 cm x 5 cm, such that the probe could be rotated at its "analytic" angle of 35.26° between the probe handle and the upper cell wall [28]. Normally the cell doors were shut, however for Figures 22 a and b, one door remained open. If the doors are both closed the 320 MHz small dip in return loss and peak in H_z are not seen. It is sufficient to cover the 1/3 of the door closest to the septum with conductive material, in order to suppress the peak. The 120.27 MHz H_z peak is seen in the large cell regardless of whether the doors are open or shut. Presumably, the TE_{01} mode requires some non-symmetry to be excited and the larger cell has more deformations than the more rigid small cell. The effective length for the TE_{011} resonance is approximately d_3; i.e., to the tips of the tapers. Figures 22 c and d show an interesting gradual rise in the field strength starting at 420 MHz and leveling off at 480 MHz with H_z = 300 $\mu A^2/m^2$ compared to an expected H_x TEM field value of 175 $\mu A^2/m^2$. This rise implies a modal propagation with a lower cutoff frequency rather than a resonant character. In Figures 22 e and f the strong peak at 565 MHz is probably the $f_{res\ (111)}$ frequency for the TE_{11} mode.

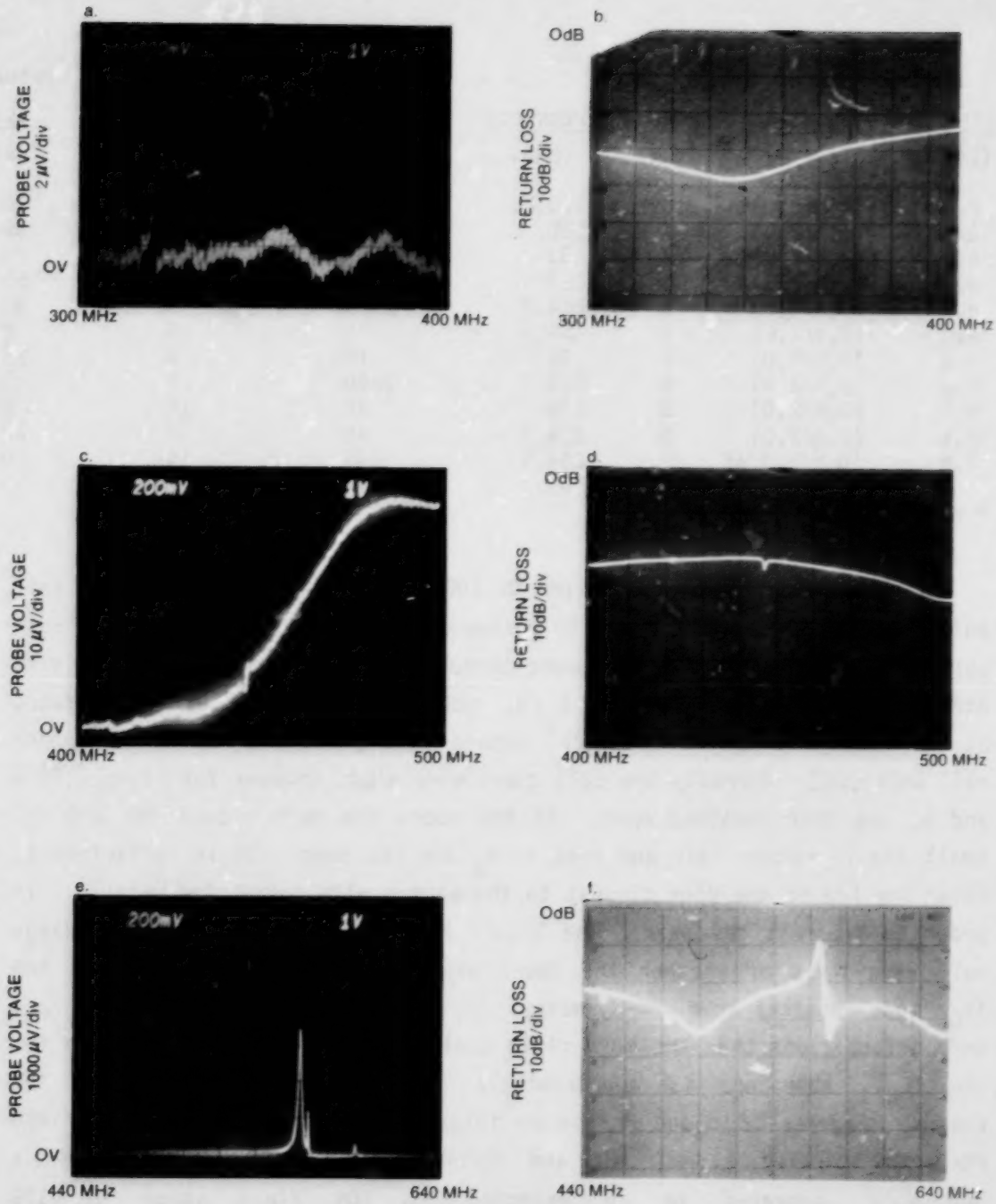


Figure 22(a-f). CC-105 cell TE measurements.

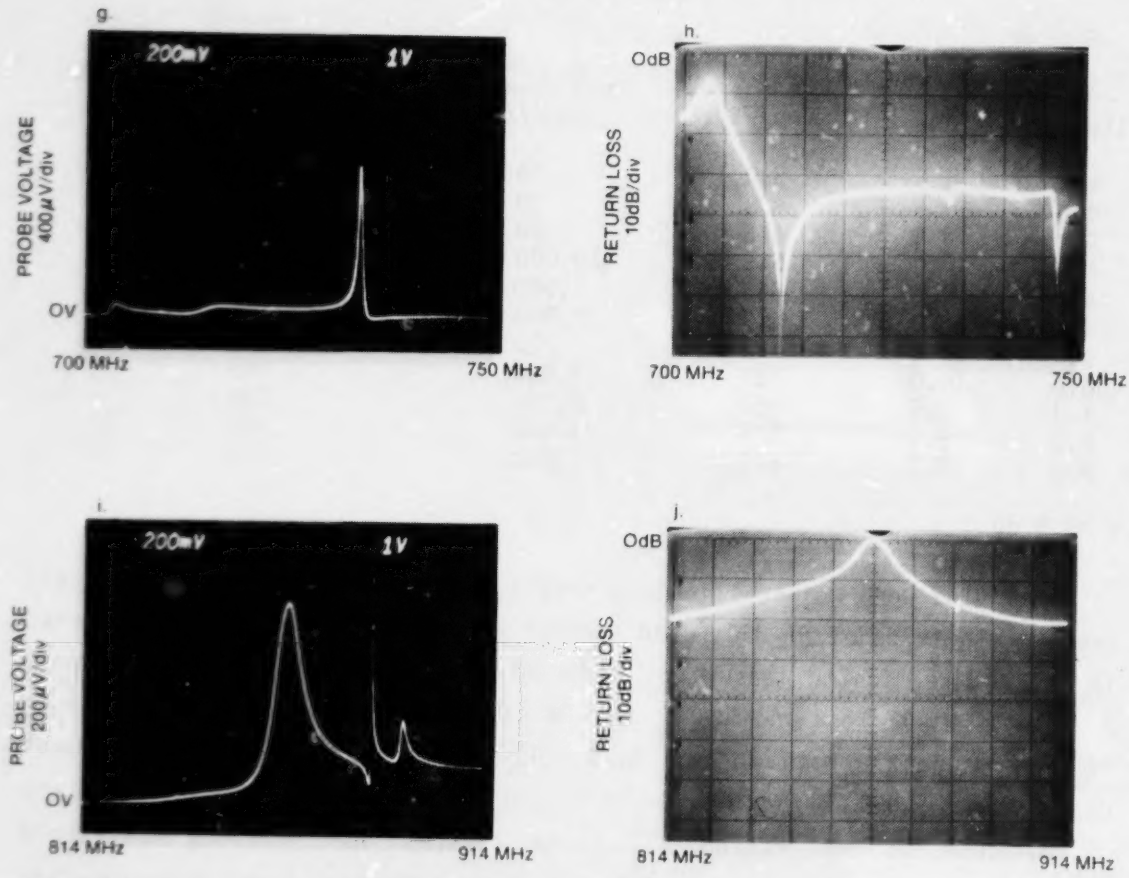


Figure 22 (g-j). CC-105 cell TE measurements.

Again, in Figures 22 g and h there is a gradual rise and leveling off of field beginning at 715 MHz and ending at the 733 MHz resonance. Between 640 and 700 MHz, and 750 to 814 MHz no marked changes in return loss and no measured H_z occurred. Table 7 summarizes the results for peaks seen in Figure 22.

TABLE 7. CC - 105 CELL TE MEASUREMENTS
(all measurements at the test point)

See Fig. 22 (letter)	Power* (dBm)	Frequency (MHz)	H_z^2 Peak Field ($\mu A^2/m^2$)	H_x^2 TEM Field ($\mu A^2/m^2$)	Return Loss (dB)
a,b	5.5	320	38	55	35
c,d	10.5	408	10	175	23
c,d	10.5	446	40	175	26
e,f	10.0	565	18,000	156	9
e,f	10.0	569.6	7,500	156	22
e,f	10.0	595	2,000	156	27
g,h	10.0	703	720	156	6
g,h	10.0	733	7,600	156	36
i,j	9.5	864	5,000	139	0
i,j	9.5	885	5,600	139	17
i,j	9.5	893	2,200	139	18

* ±0.5 dB

TM fields were measured using a single axis of a Holaday electric field probe (Holaday model HI-3001 used without associated readout meter) pointed in the z direction to measure E_z. The probe calibration is given in Table 5. The first TM resonance is at the TM cutoff frequency and is independent of the resonant length and is thus well-defined. The similarity between results in Figure 23 for the larger CC-101.5 cell and in Figure 24 for the CC-105 cell is encouraging. In both figures part (a) is the field measurement at the test point with the three principal peaks corresponding well to: $f_{res\ (110)}$ and $f_{res\ (120)}$ for the first peak, $f_{res\ (210)}$ and $f_{res\ (220)}$ for the second peak which is split, and $f_{res\ (320)}$ for the third peak. Part (b) of both figures is at the same frequency range except the probe is moved to (0,b/2,~d/4) longitudinally down the cell. At this location two new peaks appear with the previous peaks still visible. The frequencies for the peaks seen in Figure 23 b are 403, 427, 433, 472, 477, and 529 MHz. The frequencies for peaks in Figure 24 b are 1061, 1136, 1153, 1255, 1268, and 1409 MHz. A search was made for E_z peaks below these frequencies and none were found.

Automated runs were made between 100 and 150 MHz with an isotropic magnetic probe at the test point (see Section 6), the peak at 120 MHz in the larger cell was wider and less intense than in Figure 21 c. The same

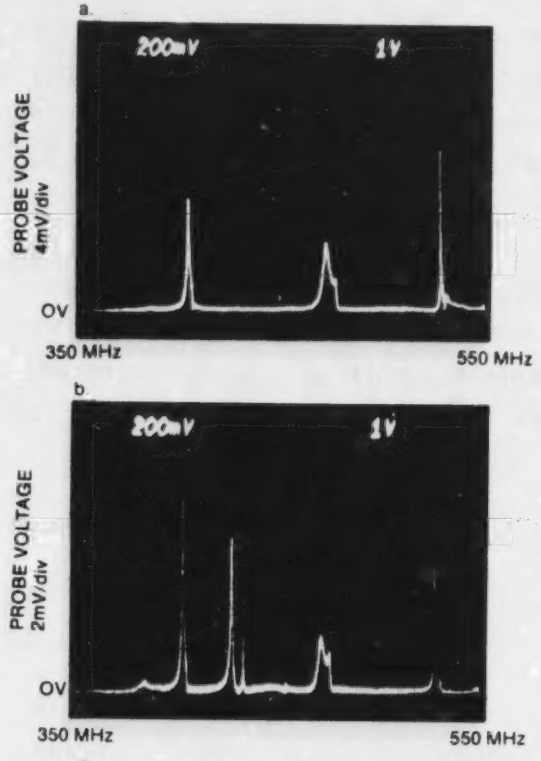
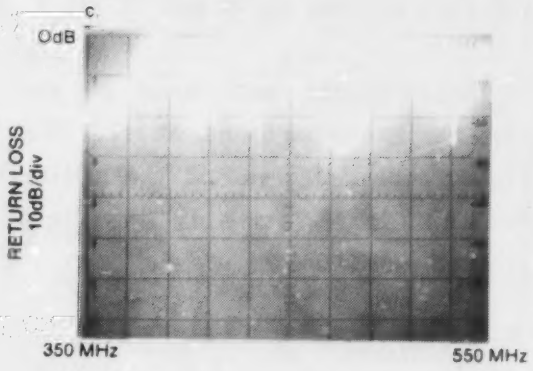


Figure 23. CC-101.5 cell TM measurements.



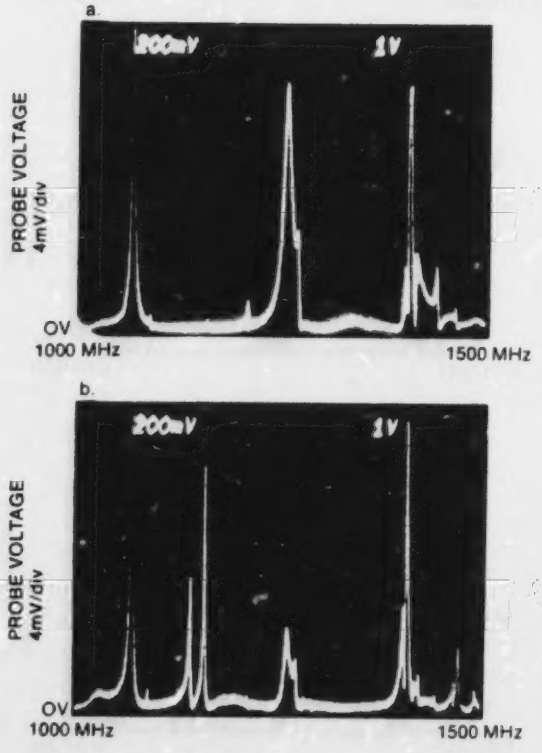
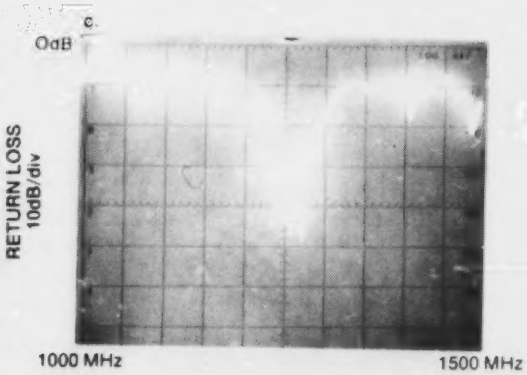


Figure 24. CC-105 cell TM measurements.



runs made with an isotropic electric probe show no peak or dip at the test point, which is reasonable since in a resonant cavity the magnetic field is strong where the electric field is weak, and vice versa [29]. If the electric field is zero due to the resonance, the TEM electric field is not affected at that point and no dip is seen.

Measurements were made of the electric field uniformity at several frequencies around and at 120 MHz in the CC-101.5 cell. An isotropic E field probe was moved in the x direction in the cell at $y = b/2$ and $z = 0$. The percent deviation in the field from its value at the cell center is plotted in Figure 25.

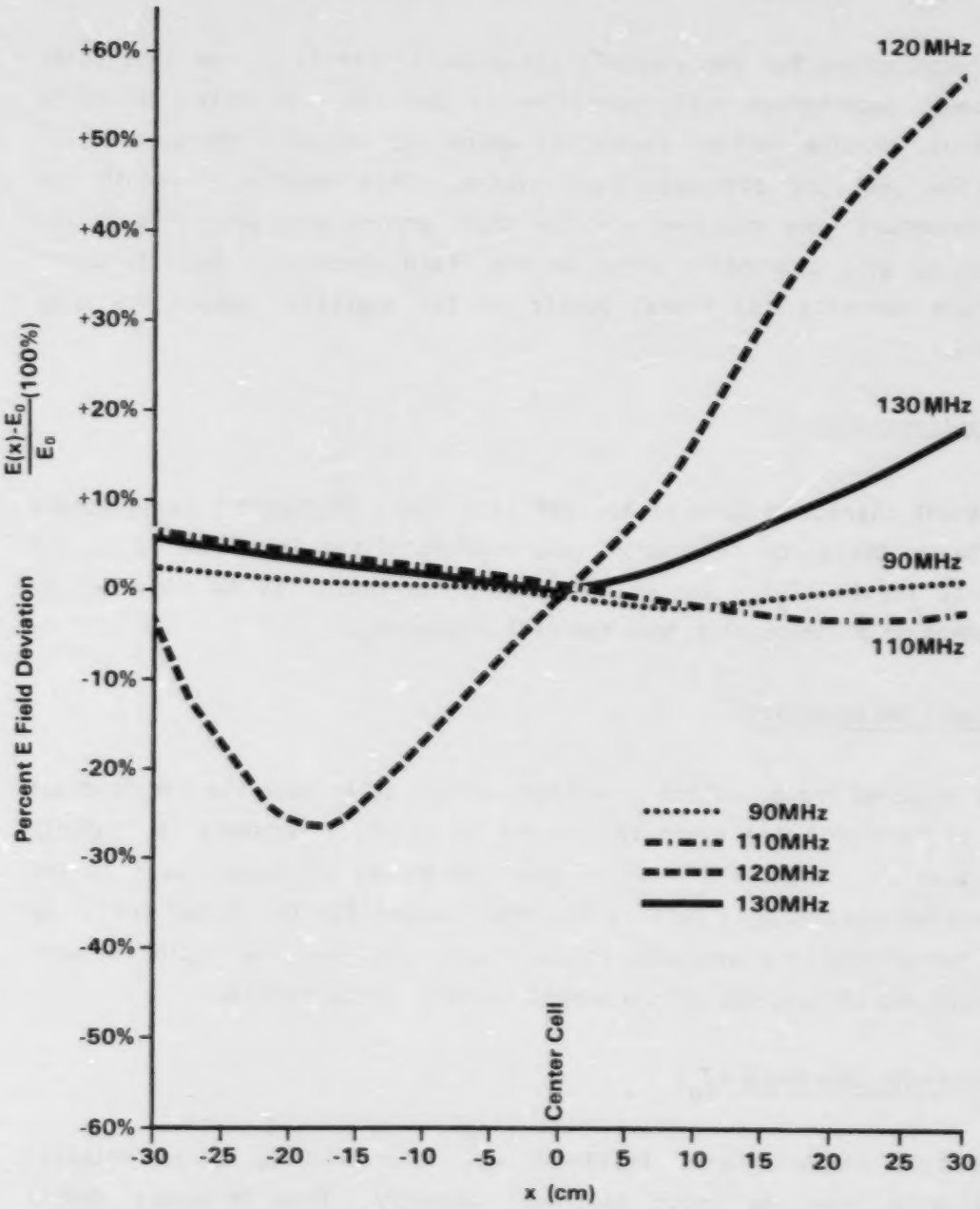


Figure 25. Isotropic probe measurement of TE_{011} resonance.

SECTION 5
CALIBRATION PARAMETER MEASUREMENT AND ERROR PROPAGATION

The expressions for the electric and magnetic fields at the test point of an empty unperturbed cell, operating in the TEM mode only, including reflections, require various parameters which are measured characteristics of the TEM cell and attenuator-load system. This section documents how these parameters were measured and how their errors propagate through the equations to give a probable error in the field strength. Absolute power measurement accuracy and signal purity at the amplifier output are also addressed.

CELL CHARACTERISTICS

Relevant characteristics of the TEM cell are: dimensional measurements particularly the plate separation (b), characteristic impedance (Z_o), and electrical length (l_e). The characteristic impedance can be obtained by measurement or theoretically from the cell dimensions.

Dimensional Measurements

The measured cross section dimensions of the cells near the longitudinal center of each cell are given in Figures 26 and 27. Accuracy is probably better than 1%. Figures 28 and 29 give the values of length used in the resonance calculations, as well as the taper angles for the larger cell. Up to 5mm variations in b are seen in the large cell over the region between the shield and septum, due to the warped surface of the shield.

Characteristic Impedance (Z_o)

The cell characteristic impedance was determined by three methods: Theoretically from the cross sectional geometry, from frequency domain reflectometry (FDR), and from time domain reflectometry (TDR).

Geometry

Using the approximate Eq. (8) and the values of a, b, and g results in a characteristic impedance of 51.1Ω for the CC-101.5 cell and 52.4Ω for the

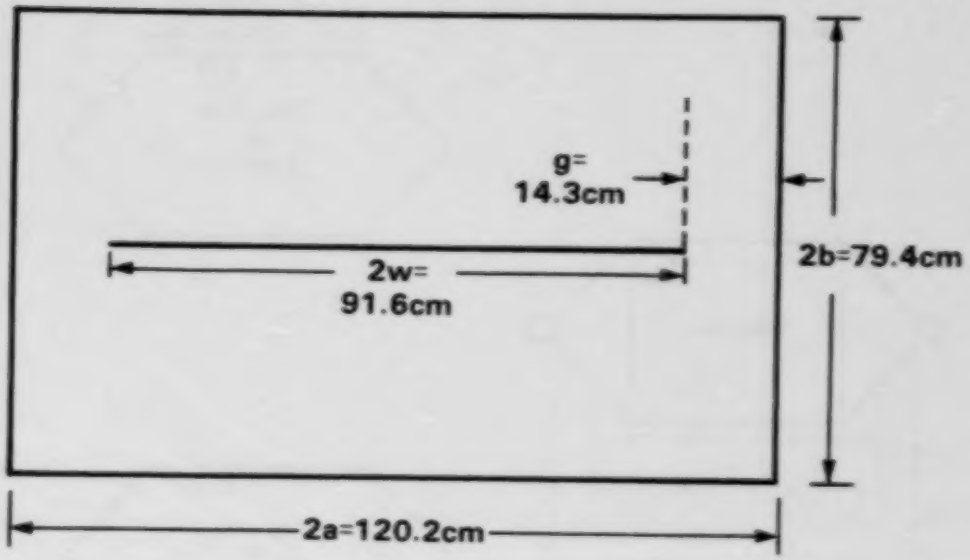


Figure 26. Cross sectional dimensions of the CC-101.5 cell.

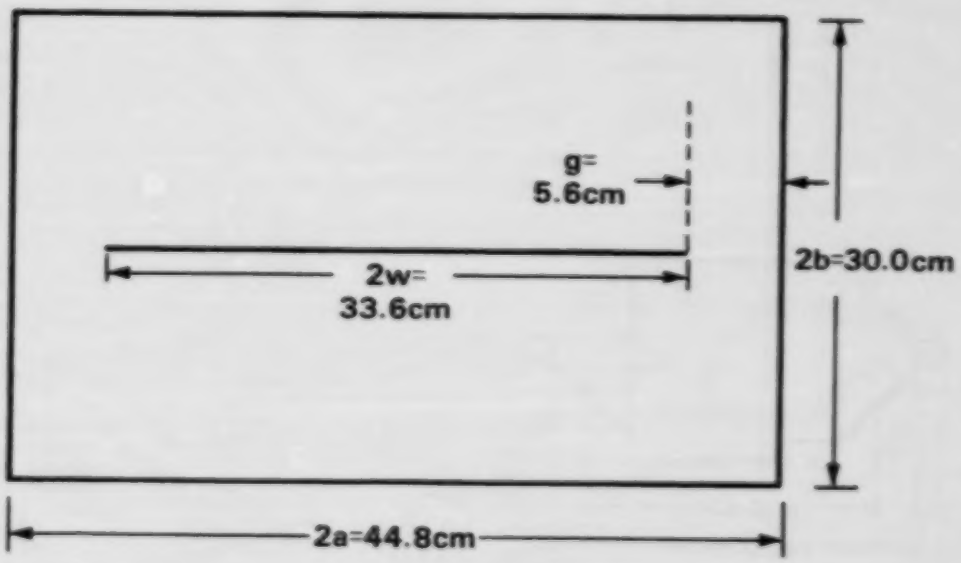


Figure 27. Cross sectional dimensions of the CC-105 cell.

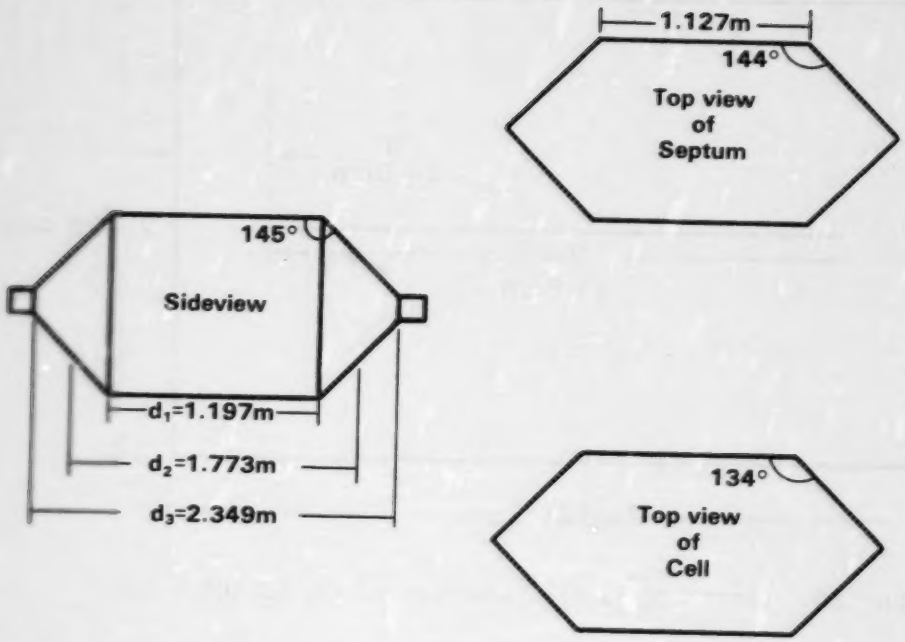


Figure 28. CC-101.5 cell dimensions.

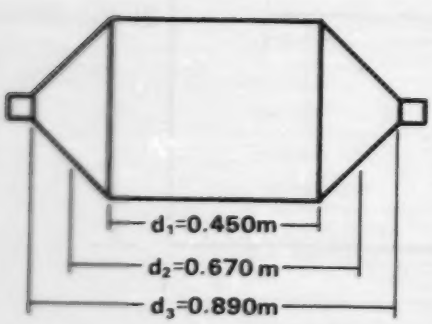


Figure 29. CC-105 cell lengths.

CC-105 cell. Results obtained using the exact elliptic functions are not significantly different for these geometries; i.e., the difference is less than 0.05 ohm.

Frequency Domain Reflectometry

A well known technique called frequency domain reflectometry (FDR) is often used where the transmission line equation simplifies at 1/4 wavelength back from the load, and Eq. (10) becomes $Z_0 = \sqrt{Z_i Z_l}$. Z_i is measured using a vector voltmeter and a directional coupler and Z_l is the known termination impedance. The results of using the technique for determining the characteristic impedance were 50.6 Ω for the CC-101.5 cell and 51.0 Ω for the CC-105 cell. These may be compared with the manufacturer's specified characteristic impedance of 50.0Ω.

Time Domain Reflectometry

A fast rise time domain reflectometry (TDR) system (<35 psec) was used with a 50 ohm standard air line. The measurements setup consisted of a Hewlett-Packard TDR unit, cable, General Radio 50 ohm air line, cell, and a 50 ohm termination in series. Figures 30 and 31 illustrate the results of TDR tests applied to the two TEM cells studied. A visual average line was drawn through the data between the tapers to result in 51.5 Ω for both cells. Since the reflections due to nonuniformity at the connector end go both positive and negative these should approximately cancel at normal operating frequencies. The large peaks seen at the far end of the plots are probably due to the fact that the fast rise time pulse includes frequencies above the cutoff frequencies for higher order modes. The same result was obtained if the cell was turned end for end and the TDR test repeated.

The results of characteristic impedance of the cells are summarized in Table 8. The uncertainty in Z_0 (0.9 Ω for the CC-105 cell) includes some effect of nonuniformity of the cell because the FDR method uses the entire cell while TDR and theoretical methods use only the central section of the cell between the tapers.

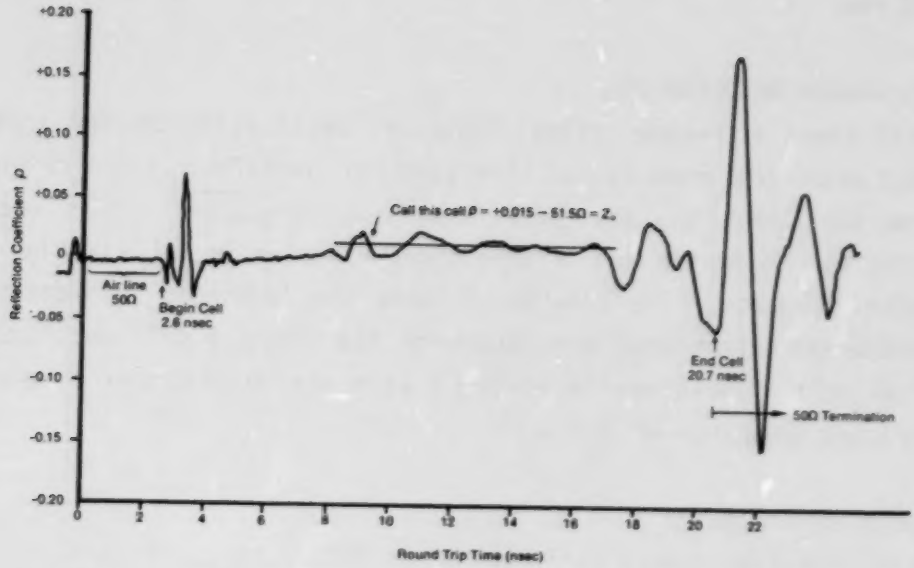


Figure 30. CC-101.5 time domain reflectometry measurement.

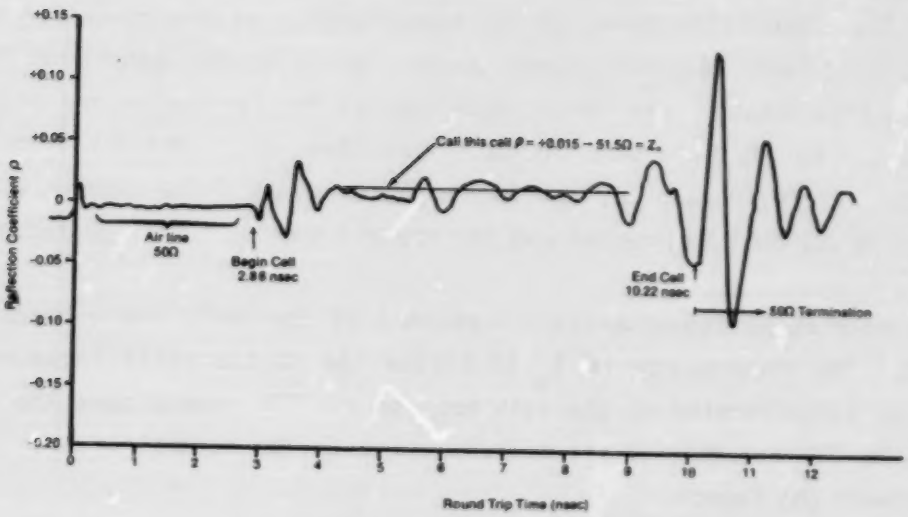


Figure 31. CC-105 time domain reflectometry measurement.

TABLE 8. CHARACTERISTIC IMPEDANCE

	CC-105 (ohms)	CC-101.5 (ohms)
Theoretical	52.4	51.1
FDR	51.0	50.6
TDR	51.5	51.5
Mean	51.6 ± 0.9	51.0 ± 0.5

Electrical Length (l_e)

Using a vector voltmeter and a dual directional coupler and shorting the output port of the cell, the lowest frequency where the forward and reflected voltage waves are in phase at the input port was found. When this condition exists, there is 1/4 wavelength from end to end of the cell. One-fourth the free space wavelength associated with that frequency is the measured electrical length of the cell. Measured results were: l_e = 1.138m for the CC-105 cell, and l_e = 2.78m for the CC-101.5 cell. The TDR plots give approximate confirmation with 1.10m for the CC-105 cell and 2.72m for the CC-101.5 cell. The FDR results are used because of their greater intrinsic accuracy. The FDR method is more accurate because it is a nulling technique using a known frequency source. The TDR method depends on the time domain accuracy of an oscilloscope.

LOAD CHARACTERISTICS

The present high power load or attenuator system used is built from two (2) attenuators and two (2) cables (see Appendix C for details). These components form a two-port device having a nominal attenuation of 43 dB, maximum continuous power handling capability of 2 kW, and a maximum measured input VSWR of 1.10, output VSWR maximum is 1.06 below 220 MHz. A directional coupler is not used to measure the power through the cell. The attenuator output is connected to three (3) possible power sensors through a pair of microwave switches. Insertion loss through the switches is negligible (< 0.02dB) below 220 MHz. The absolute power meter reading with

the known attenuation is used to determine the power through the cell. The measured load impedance (Z_1) is used to correct the fields in the cell for standing waves.

Attenuation

The most critical measurement is the attenuation or insertion loss of the attenuator system. The power ratio method was used. Mismatch error and non-linearity of the power meter used are the primary sources of error in such a measurement. Variation in source power during the measurements was <0.02 dB. Using techniques described in a Hewlett-Packard Application Note [30] the maximum mismatch error for the calibration and insertion measurement can be determined from the maximum source, detector, input, and output VSWR's. Above 10 MHz, to reduce error due to power meter non-linearity, the system was considered as two parts: (1) the high-power input cable into the 30dB, 2kW attenuator, and (2) the output cable into a low power 13dB attenuator. Thus, two attenuation measurements are made and added together. The source VSWR was reduced to <1.04 by using amplification and a 20 dB pad. The detectors were selected to give a maximum detector VSWR of 1.08 at 10 MHz. For the high power section, input VSWR was <1.10 and output VSWR was <1.12 resulting in a maximum mismatch error of ±0.03 dB. The low power section input VSWR was <1.06 and output VSWR was <1.02, giving a maximum mismatch error of ±0.02 dB. Adding these together gives a maximum total mismatch error of ±0.05 dB. Typical values are much less. Measurements made with a Fluke model 5101A calibrator indicated a maximum power meter non-linearity of ±0.05 dB for each of these measurements.

The total attenuation measured is shown in Figure 32 as a function of frequency. Significant mismatch errors would be seen as oscillations in the measured value and are not observed indicating small mismatch errors. Below 10 MHz a terminated RF millivoltmeter was used and accuracy was greater. A least squares fitted attenuation curve, the dashed line in Fig. 32, was used in the system computer control program. Confidence in the attenuation obtained by this approach is ±0.2 dB. The attenuator system was sent to the National Bureau of Standards (NBS) for measurement of attenuation and complex input impedance. NBS attenuation measurements between 500 kHz and 220 MHz matched EPA measurements to within ±0.15dB worst case.

All of these attenuation measurements were made at low power. Measurements by the manufacturer and confirmed in this study, showed, however, a decrease in attenuation of up to 0.28 dB at high power levels (up to 2 kilowatts) and high frequency. High power levels result in significantly elevated attenuator temperatures and a changed attenuation. An additional error of ±0.28 dB is included in the attenuation to give ±0.48 dB total attenuation error at high power. Such changes of attenuation with temperature suggest the desirability of changing to a directional coupler in the next generation system to measure power for reducing calibration uncertainties.

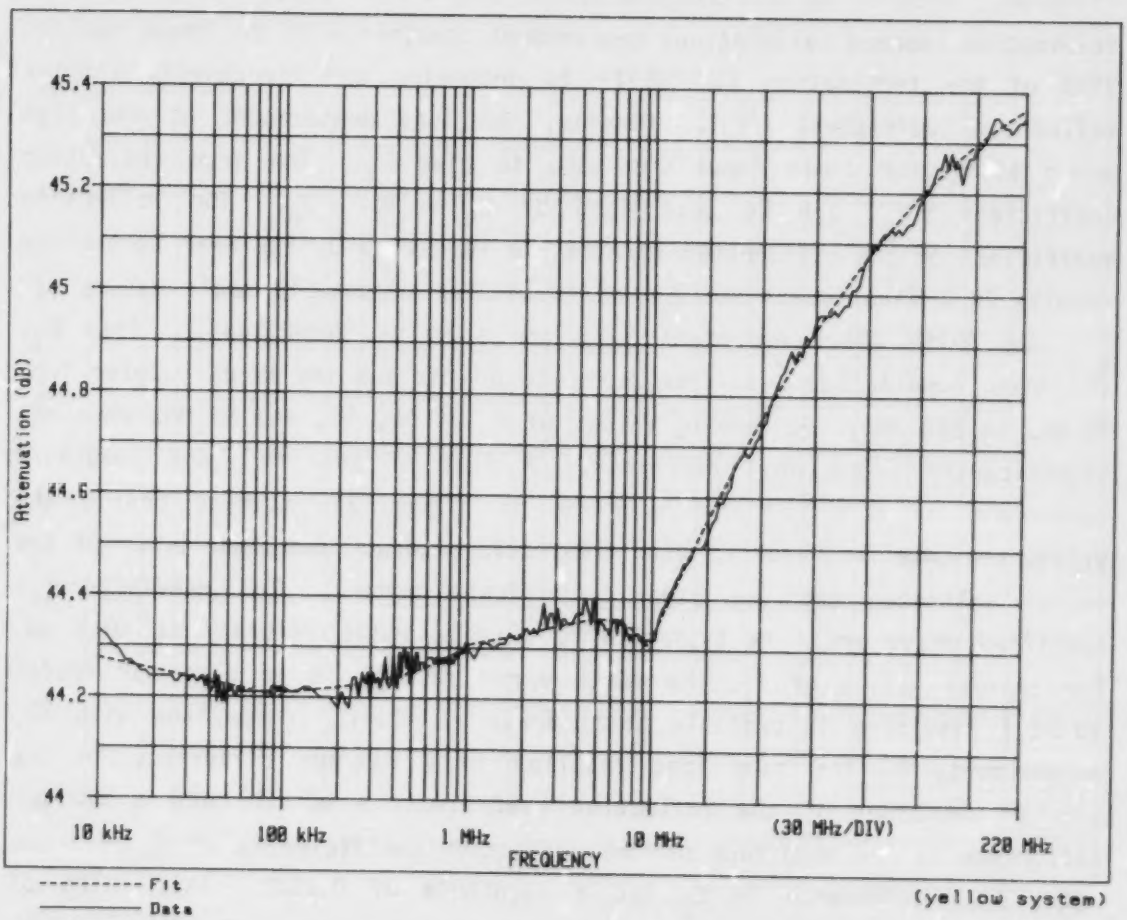


Figure 32. Attenuation characteristics of high power load system.

Complex Impedance

A vector voltmeter was semi-automated with an analog to digital converter interfaced through the IEEE-488 bus to a desktop computer. A program listing is given in Appendix A. The measurement technique was as described in a Hewlett-Packard Application Note [31] for 100 MHz to 1000 MHz. This technique involves two calibration measurements and one load measurement of complex reflection coefficient. A synthesizer under computer control drives an amplifier and attenuator to give a nominal signal power of 100 mW and low source VSWR. This source drives a dual directional coupler, either a 0°, Narda model 3020A or a 180°, Anzac model CD-920-4. The first calibration measurement using a coaxial short establishes the coupling difference between the two sidearm ports, and a 180° phase reference. The termination (second calibration) measurement combines with the known maximum VSWR of the termination (<1.0027)* to determine the directivity complex reflection coefficient (Γ_d). Finally, the load measurement at the high power attenuator cable input was made to give Γ_1. The true reflection coefficient (Γ_t) can be determined by $\Gamma_t = \Gamma_1 - \Gamma_d$. The reflection coefficient of the calibration termination is called 0, its near zero value results in a final error of Z_1 of $\pm 0.14\Omega$ for reasonably small values of Γ_t. The Smith chart equations [32] are used to determine Z_1 from Γ_t. The Anzac coupler was used from 1 MHz to 60 MHz and the Narda coupler from 50 MHz to 220 MHz; overlapping values of Z_1 at 50, 55, and 60 MHz were not significantly (<0.2 ohm) different. A plot of the real and imaginary components of $Z_1 = R_1 + jX_1$ is given in Figure 33, numbers beside the points indicate frequency in MHz. The ratio accuracy and phase error of the vector voltmeter are two other significant errors. The manufacturer's specified phase error is typically ±1°, while ratio accuracy is ±0.3 dB. For typical values of Z_1, the ratio error results in an error of $\pm 0.25\Omega$ in $|Z_1|$ resulting in probable total error of $\pm 0.4\Omega$. Comparison with NBS measurements on the same load resulted in a maximum difference in the angular component of the reflection coefficient θ of 17° and a maximum difference in the magnitude of the reflection coefficient ρ of 0.004. The worst case difference in Z_1 had a magnitude of 0.85Ω. This value of $\pm 0.85\Omega$ is used as a conservative estimate of the error in Z_1. Temperature stability for the load input impedance has not been determined.

* All references to maximum VSWR apply to frequencies $\leq$ 220 MHz.

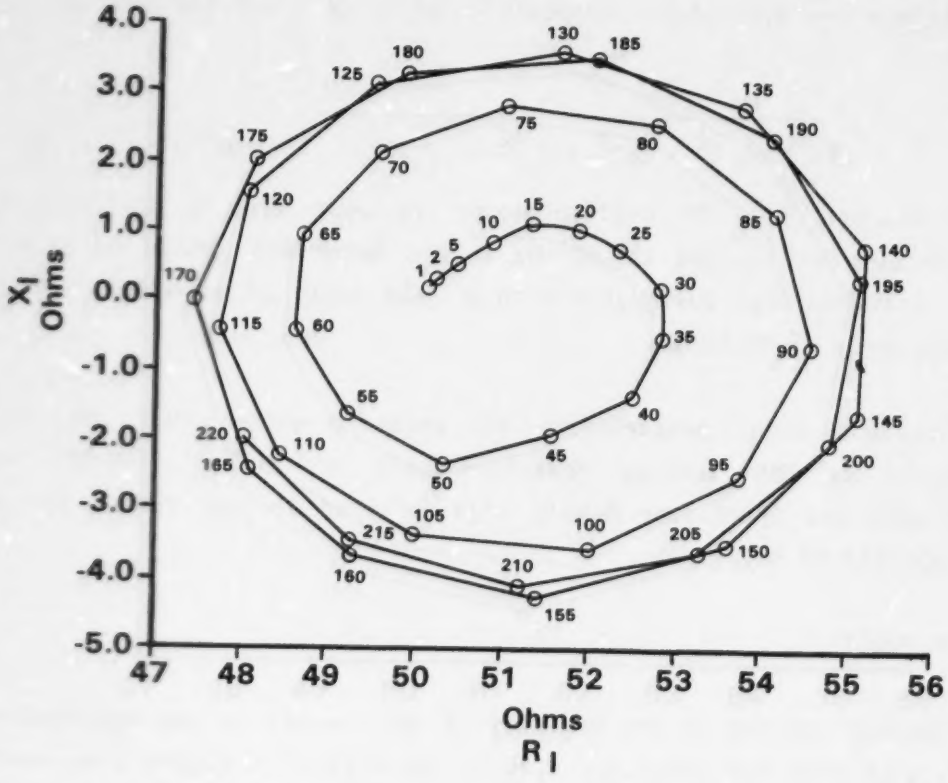


Figure 33. Load impedance. Numbers beside the points indicate frequency in MHz.

POWER METERS

For absolute power (P_m) measurement at the attenuator output port above 10 MHz a Hewlett-Packard model 436A power meter with a model 8481A power sensor is used between -20 and + 20 dBm. The 8484A power sensor is used below - 20 dBm. This error analysis follows closely Hewlett-Packard "Power Meters and Sensors" technical data 8/1/81. Maximum mismatch err[illegible]s ±0.6%. Calibration factor variations be.ow 220 MHz are less than [illegible]. Power reference uncertainty is ±0.7%. A calibration pad used only with the 8484A sensor adds ±1.1%. Instrumentation uncertainty and sensor power

linearity adds ±1.7% . Zero set, noise, and power reference mismatch uncertainty are 0.2% each. Probable total error (root-sum-square) is given by

$$\sqrt{0.6^2 + 1^2 + 0.7^2 + 1.7^2 + (0.2)^2 \cdot 3} = \pm 2.46\% \text{ or } \pm 0.11 \text{ dB}$$

A Boonton 9200 RF millivoltmeter is used with a 50 Ω feed-through termination from 10 kHz to 10 MHz. This meter was tested using a Fluke model 5101A voltage calibrator with a wide band option which indicated a maximum error of ±0.10 dB.

Thus all power measurements are probably within ±0.11 dB (±2.5%) traceable to NBS through Hewlett-Packard or Fluke. Thermal voltage converters and thermistor mounts will be used in the future for direct traceability to NBS.

SIGNAL PURITY

Implicit in much of the analysis of this report is the requirement that the signal from the generator (linear amplifier) is a pure sine wave at a single fixed frequency. However, harmonic distortion at high-power levels and noise at low-power levels limit the dynamic range over which a sine wave is well approximated.

Harmonic Distortion

A high power 110 MHz low pass filter is always used at the input of the CC-101.5 cell to keep harmonic distortion small at multimode resonant frequencies. The limited bandwidth of the amplifier is adequate to keep such harmonics small when using the CC-105 cell. Low pass filters at 30 MHz and 60 MHz are also used if the operating frequencies are low enough. Second harmonics within the TEM bandwidth of the cells may be as large as 17 dB below the fundamental leading to a ±2% or ±0.08 dB power error worst case.

Noise

Harmonics of the 60 Hz power line frequency are more important than thermal noise in limiting dynamic range. This power supply noise is documented in Figures 34 through 37. The linear amplifier input was terminated in 50 Ω and gain was set to maximum. Figures 34 and 35 show the noise at the 100 watt output; Figures 36 through 37 show the 1 kW output noise. At each amplifier output a 20 dB 50 Ω attenuator was used and both the oscilloscope and spectrum analyzer have 50 Ω inputs. To obtain the actual output voltage, multiply the scope voltage by 10. To obtain output power, add 20 dB to the values indicated in dBm. Figure 34 a and b show the time domain noise, into a 50 MHz bandwidth oscilloscope, at the 100 watt output. Peak voltage is about 260 mV. Spectrum analysis at the 100 watt output is given in Figure 35 a, b, c, and d; b and c are samples over a 3 kHz span; d shows the thermal noise over the full bandwidth of the amplifier. Figures 36 and 37 give similar information at the 1 kW output. A practical check is to operate the amplifier with the input terminated and see if the survey instrument being calibrated in the TEM cell responds.

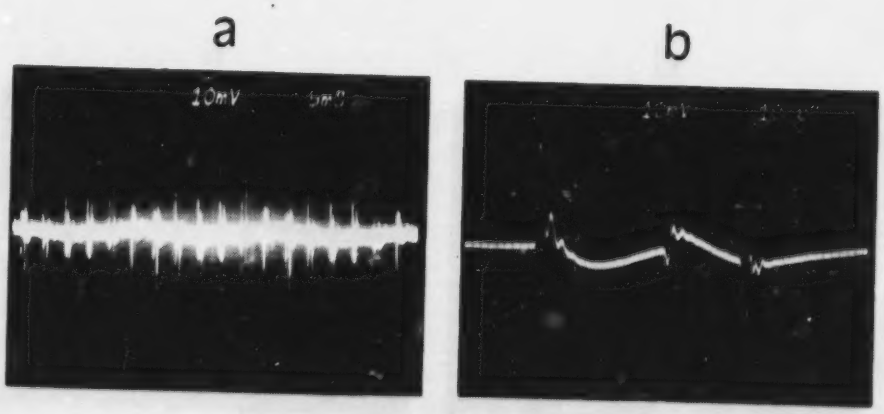


Figure 34. Time domain noise at 100 watt output.

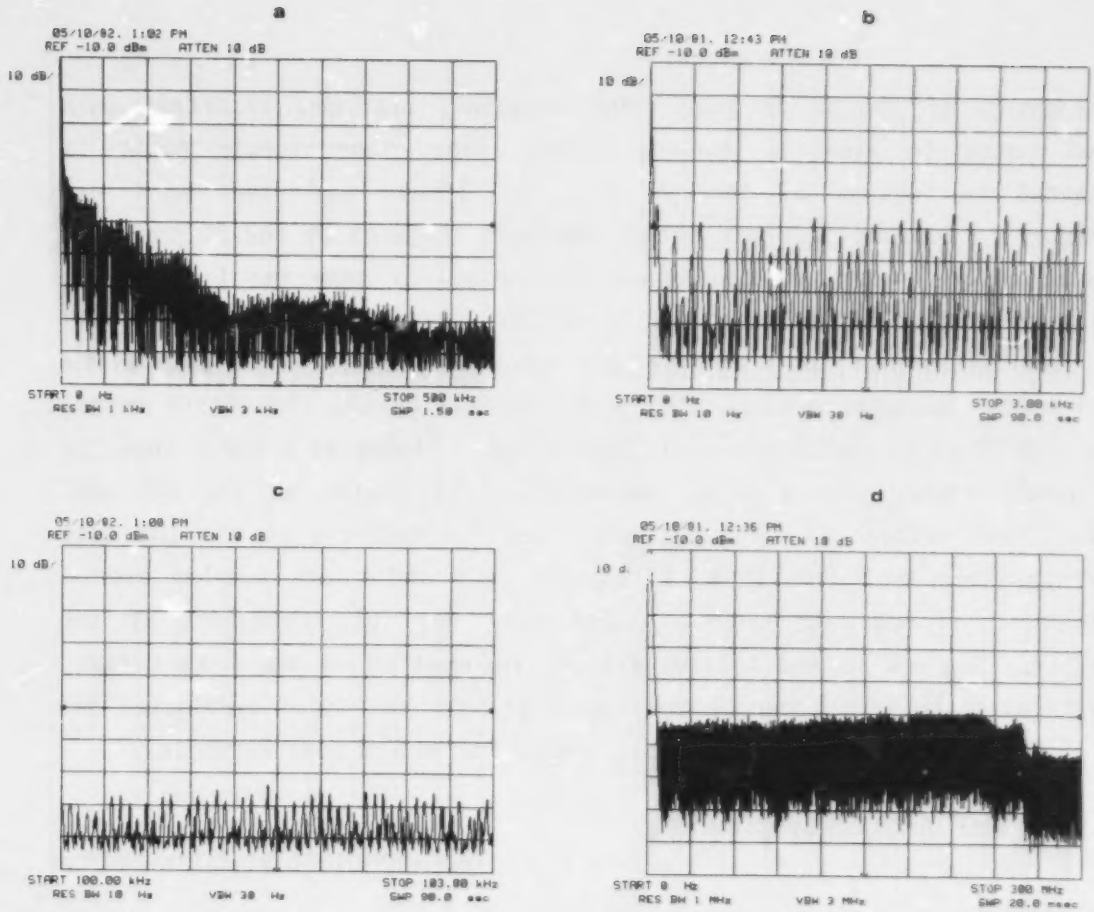


Figure 35. Frequency domain noise at 100 watt output.

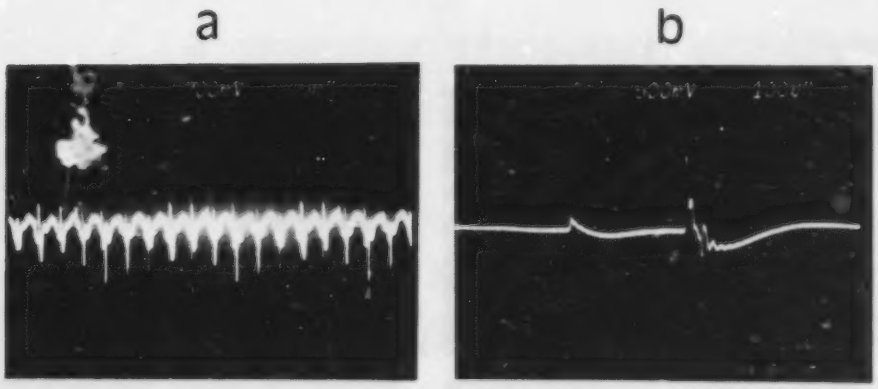


Figure 36. Time domain noise at 1 kW output.

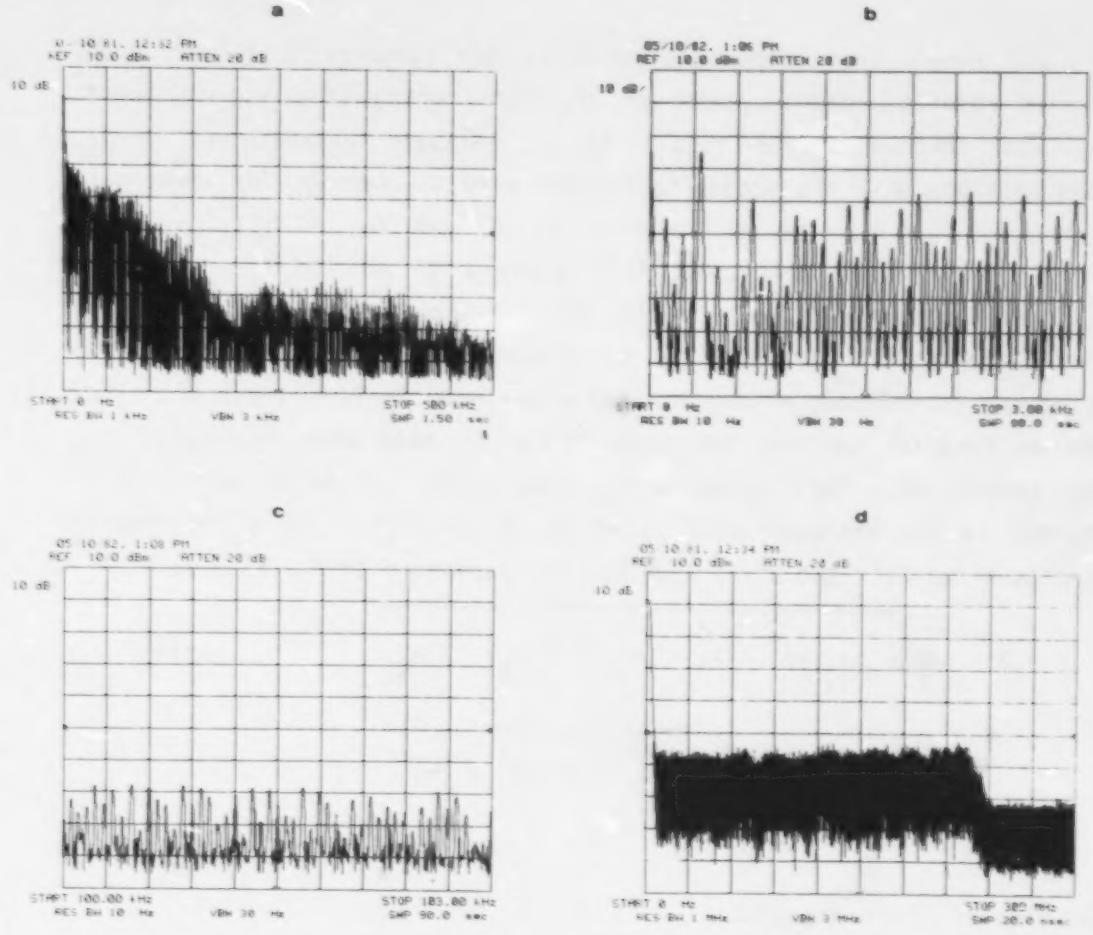


Figure 37. Frequency domain noise at 1 kW output.

ERROR PROPAGATION

From equation 14 and $P_n = P_m \cdot A$, the formula for the electric field strength squared (proportional to power) is

$$E^2 = \frac{|Z_i|^2 \cdot P_m \cdot A}{b^2 \cdot R_i} \quad \underline{\text{at}} \text{ the test point,} \tag{33}$$

where each parameter has some percentage error. When the factors are multiplied or divided the error is propagated using the root-sum-square (RSS) of the individual percentage errors. The error is multiplied by the power when powers or roots are taken [33]. This error propagation step

assumes all errors are independent which is not strictly true because Z_i and R_i are related, however, most of the terms going into it are "worst case". This method should result in a realistic estimate of error. Previous sections give the needed individual errors. Adding, for worst case error in $|Z_i|$ or R_i, the $\pm 0.9\,\Omega$ error in Z_o and the $\pm 0.85\,\Omega$ error in Z_1, for values of Z_i near 50Ω, this gives a 4% or $\pm 2\Omega$ error in $|Z_i|$ or R_i. A maximum error in b is $\pm 1\%$. Absolute power measurement uncertainty is $\pm 2.5\%$. The ability to measure power (P_m) also includes a $\pm 2\%$ error due to harmonic distortion and a maximum of $\pm 2.3\%$ (± 0.1 dB) error allowed in computer setting the power meter to read what its calculated reading should be. This gives a P_m uncertainty of $\pm 6.8\%$ worst case. Uncertainty in the attenuation A is ± 0.48 dB or $\pm 12\%$. If Δ_x represents the percent error in x the error equation corresponding to Eq. (33) is:

$$\Delta_{E^2} = \sqrt{(2\cdot\Delta_{|Z_i|})^2 + \Delta_{P_m}^2 + \Delta_A^2 + (2\cdot\Delta_b)^2 + \Delta_{R_i}^2} \qquad (34)$$

$$= \sqrt{(2\cdot 4)^2 + (6.8)^2 + (12)^2 + (2\cdot 1)^2 + (4)^2}$$

$$= 16.56\% \text{ or } \pm 0.79 \text{ dB}$$

for the electric field squared.

Similarly for the magnetic field squared:

$$H^2 = \frac{Z_o^2 \cdot P_m \cdot A}{b^2 \cdot 377^2 \cdot R_i} \qquad (35)$$

$$\text{so } \Delta_{H^2} = \sqrt{(2\cdot\Delta_{Z_o})^2 + \Delta_{P_m}^2 + \Delta_A^2 + (2\cdot\Delta_b)^2 + \Delta_{R_i}^2}$$

$$= \sqrt{(2\cdot 2)^2 + (4.5)^2 + (12)^2 + (2\cdot 1)^2 + (4)^2}$$

$$= 15.04\% \text{ or } \pm 0.71 \text{ dB}$$

So, the probable error in the fields is ±0.79 dB at the test point of either empty unperturbed cell operating in the single TEM mode only. The section on TEM fields throughout the cell cross section (Figures 11 and 12) gives information on the field variation in a circular zone occupied by the probe due to misplacement and physical size of the probe. If the radius of this circle were 5 cm this error would be ±0.4 dB for the small cell and ±0.15 dB for the large cell. This error is in addition to the ±0.79 dB error at the test point and should be evaluated for the particular probe, position accuracy, and cell used. The field increases on approaching the septum and decreases when approaching the shield vertically from the test point, so the effect of the field gradient is probably smaller than the above would imply.

There are practical problems due to the non-ideal nature of survey probes which affect the ability to use them as transfer standards between different calibration systems. For example, depending on the angle of insertion into a cell, an electric field probe will usually read higher as the portion of the handle near the probe end is aligned with the electric field. Also a given probe normally reads higher in a smaller cell as if a conductive slab were between the plates. Both problems are caused by the probes perturbation of the empty cell field and its tendency to detect that peturbed field. These are not problems in the calibration systems but characteristics of the device under test. These effects are illustrated in the final section on testing and sample applications.

SECTION 6
TESTING AND SAMPLE APPLICATIONS

This section includes a few important test runs on the system operation and some sample outputs which illustrate the system's applicability to measurement probe evaluation. It is not an attempt to give extensive test data on all available meters.

COMPARISON OF PROBE RESPONSE WITH AND WITHOUT IMPEDANCE CORRECTION

A first approximation for the line impedance (Z_i) in the cell is to set the cell characteristic impedance (Z_o) and the load impedance (Z_l) equal to 50Ω pure real. This considerably simplifies the expressions for field strength and eliminates the need for impedance measurements. Figures 38 and 39 show the result of not using and using the standing wave corrections respectively. For this particular system, deviations up to 0.45dB can be seen and the probe response would be incorrectly concluded to oscillate with frequency. The complete outputs are given in Appendix D.

COMPARISON OF PROBE RESPONSE USING TWO DIFFERENT TEM CELLS

Since the field is less uniform in the smaller cell different results might be expected over a frequency range in which both cells are operating properly. Figures 40 and 41 show results for the large and small cells respectively. The meter response is typically 0.2dB higher in the smaller cell. This response may be explained by the loading effect of the probe on the cell. This effect is equivalent to reducing the septum to shield separation distance thus increasing the field strength.

A simple model useful as a first attempt at quantifying this effect is an infinite conductive slab of thickness (t) between infinite parallel plates of separation (b) and applied voltage (V). The probe or meter is modeled as a slab having some constant equivalent thickness (t). The electric field (E) is given by:

$$E = \frac{V}{b-t}$$

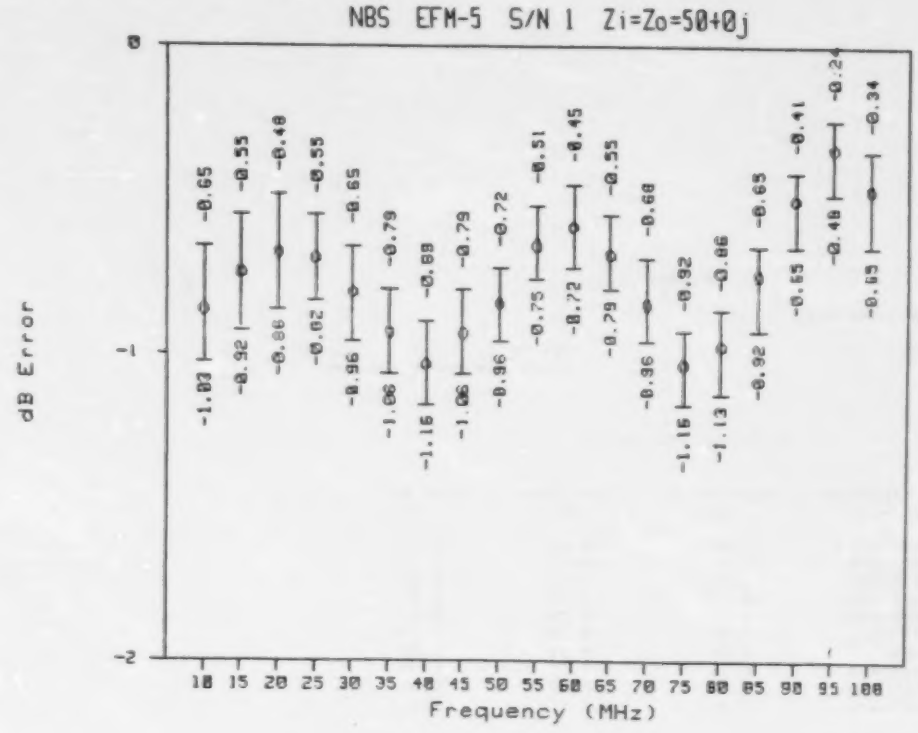


Figure 38. Field strength probe response without impedance correction.

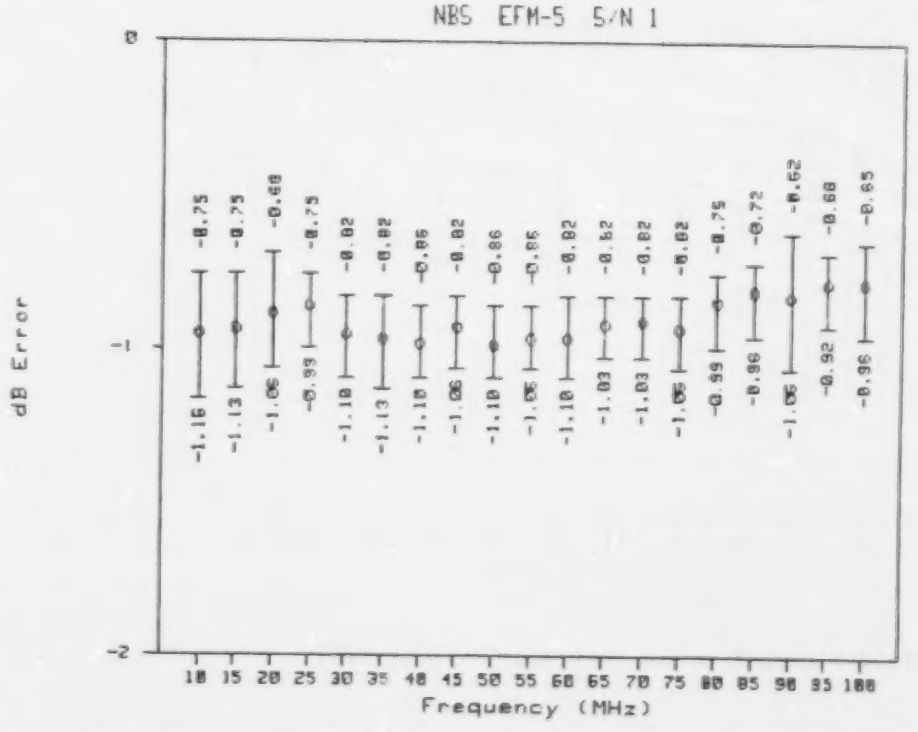


Figure 39. Field strength probe response with impedance correction.

HOLADAY 26026

Friday November 20, 1981 6:20 PM

Operator: MANTIPLY, E. D

TEM Cell: CC-101.5 (Large)
Driver Amplifier Output

Rotation Statistics

Freq. (MHz)	Avg. Reading (V)/m))	Avg. Error (dB)	Low Error (dB)	High Error (dB)
10.00	5005.630	0.00	-0.41	0.29
20.00	5077.690	0.07	-0.31	0.34
30.00	5070.340	0.06	-0.21	0.37
40.00	4938.130	-0.05	-0.34	0.17
50.00	5018.620	0.02	-0.21	0.34
60.00	5093.860	0.08	-0.18	0.37
70.00	5284.110	0.24	0.03	0.50
80.00	5193.410	0.16	-0.03	0.34
90.00	5256.690	0.22	0.03	0.37
100.00	5437.190	0.36	0.12	0.64

Applied Field = 5000 V)/m)

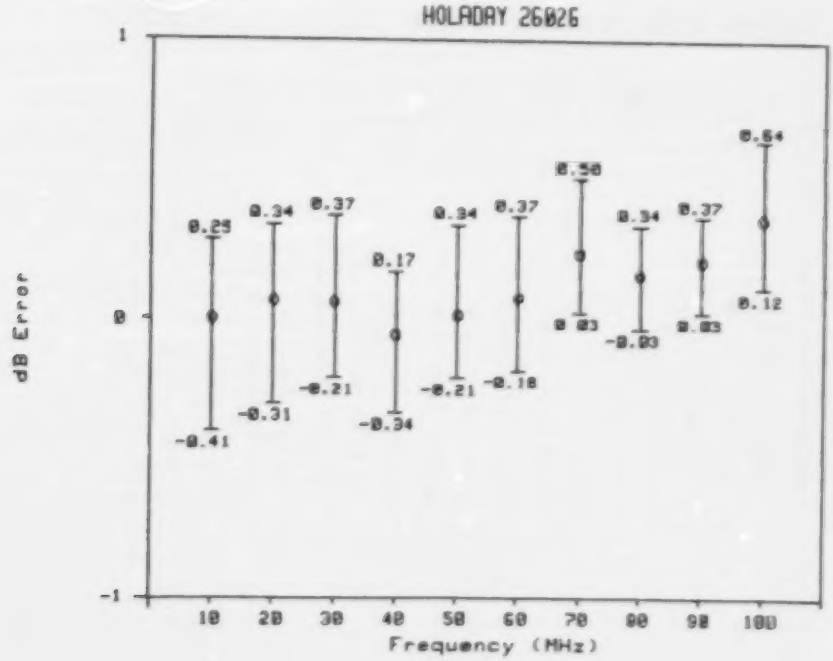


Figure 40. Field strength probe response in large cell.

HOLADAY 2[illegible]

Friday November 27, 1981 4:04 PM

Operator: MANTIPLY, E. D.

TEM Cell: CC-105 (Small)
Driver Amplifier Output

Rotation Statistics

Freq. (MHz)	Avg. Reading (V^2/m^2)	Avg. Error (dB)	Low Error (dB)	High Error (dB)
10.00	5315.100	0.27	-0.06	0.50
20.00	5408.500	0.34	0.09	0.58
30.00	5523.120	0.43	0.20	0.69
40.00	5515.950	0.43	0.15	0.71
50.00	5499.390	0.41	0.17	0.69
60.00	5464.940	0.39	0.12	0.58
70.00	5510.470	0.42	0.12	0.66
80.00	5487.390	0.40	0.12	0.61
90.00	5510.710	0.42	0.17	0.61
100.00	5364.870	0.31	0.09	0.56

Applied Field = 5000 V^2/m^2

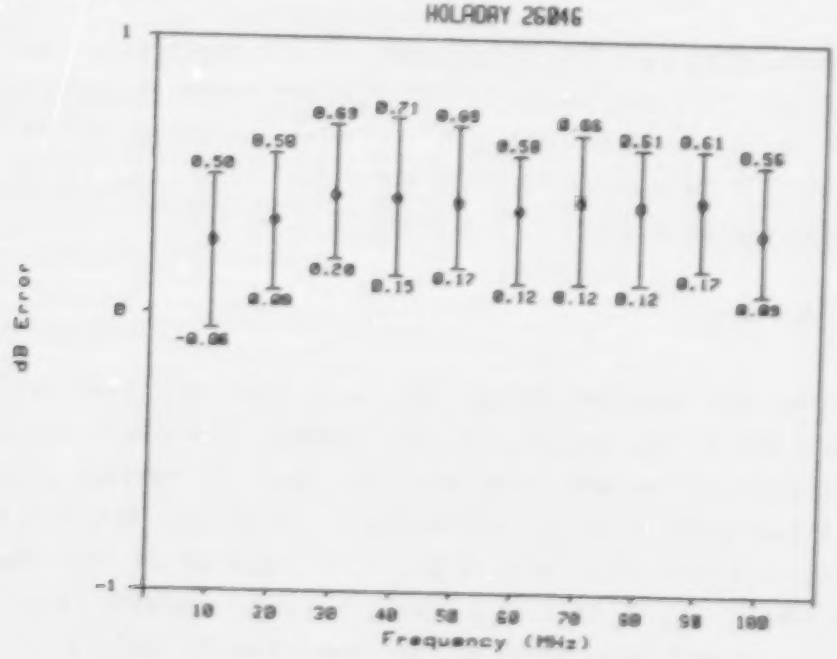


Figure 41. Field strength probe response in small cell.

If b_1 and b_2 and V_1 and V_2 are the plate separation and voltages for two systems and t is assumed to be zero and the fields are set equal then:

$$\frac{V_1}{V_2} = \frac{b_1}{b_2}$$

Now, if t is not zero the ratio of the field E_1 in system 1 to E_2 in system 2 is given by:

$$\frac{E_1}{E_2} = \frac{b_1}{b_2} \frac{(b_2 - t)}{(b_1 - t)}$$

solving for t gives:

$$t = \frac{b_1 \, b_2 \, (E_1/E_2 - 1)}{b_2 \, (E_1/E_2) - b_1}$$

Modeling the two cells as parallel plates with system 1 the smaller cell and system 2 the larger cell and using 0.2 dB for the ratio of E_1/E_2 = 1.023 and b_1 = 15 cm, b_2 = 40 cm then the equivalent thickness of the probe is t = 0.53 cm. If this model is valid the calibration error in the large cell versus free fields would be $[b_2/(b_2-t)-1]$ 100 or 1.3%.

PROBE ORIENTATION CHANGES

Usually the probes are inserted through the side door of either cell with the shaft parallel to the septum. A more standard procedure is to insert at the "analytic" angle such that when the shaft is rotated each probe element is at some point parallel to the field. A Holaday Industries model HI-3001 electric field probe with 5,000 V^2/m^2 applied at 100 MHz was rotated in the smaller CC-105 cell at a parallel and an analytic angle. Four repeats were made at each orientation and are summarized in Table 9.

TABLE 9. PROBE ORIENTATION CHANGES

Parallel Rotation			Analytic Rotation		
Average Error (dB)	Low Error (dB)	High Error (dB)	Average Error (dB)	Low Error (dB)	High Error (dB)
0.30	0.09	0.56	0.53	0.34	0.79
0.28	0.09	0.50	0.52	0.32	0.79
0.27	0.09	0.50	0.53	0.32	0.79
0.30	0.09	0.56	0.55	0.34	0.79

The meter read higher on the average with the analytic rotation but the isotropicity was not significantly different. This difference between parallel and analytic position is probably due to perturbation of the E field by the probe handle, or pickup on the leads parallel with the E field at the analytic angle insertion.

PROBE POTENTIAL SENSITIVITY

It has been observed that diode based meters having a separate probe and metering instrument may operate poorly toward the lower end of their specified frequency range. The entire instrument appears to act as an antenna or alternatively the instrument senses the potential difference in the field between the meter and the probe. The problem appears to be negligible above 10 MHz in frequency. This may be caused by the radiation source impedance of the probe element becoming comparable in magnitude to the source impedance of the high resistance leads at low frequency [34]. Using high resistance lead as a replacement for the wire element in an active monopole antenna seems to confirm this concept. At low frequency (100 kHz) the antenna performs as if the wire element is in place, at VHF (100 MHz) it performs as if no element is in place.

In order to measure this potential sensitivity a modified version of the system operating program was created. In this version the probe was not rotated but was manually moved vertically in the CC-101.5 cell such that it was at the approximate center or test point (C), touching the shield or ground (G), at the center again (C), touching the septum (S), returned to

center and repeated at each frequency. The actual vertical variation in the field is approximately 0.8dB (see Figure 14). As can be seen in Figure 42, the meter variation approaches the actual field variation at higher frequencies.

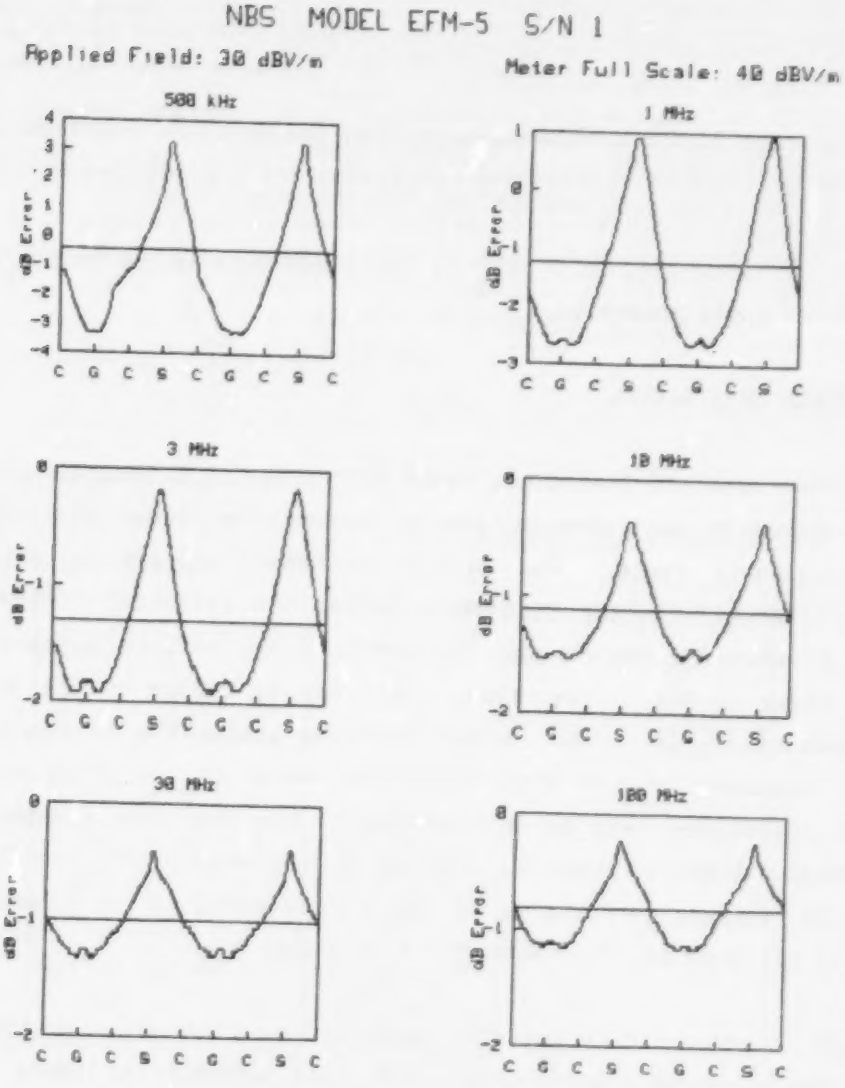


Figure 42. Field strength probe potential sensitivity.

MODAL EFFECTS IN LARGE CELL

Using the normal operating program, the effect of the TE_{01} resonance at 120 MHz in the large cell can be seen with an isotropic magnetic field probe (see Figure 43). This peak is not seen with the same probe in the small cell. Also the 120 MHz peak is not seen with an electric field probe at the large cell test point. The peak is about 2.5dB above the surrounding data at other frequencies. This result emphasizes the need to determine the modal characteristic of cells used for probe calibrations.

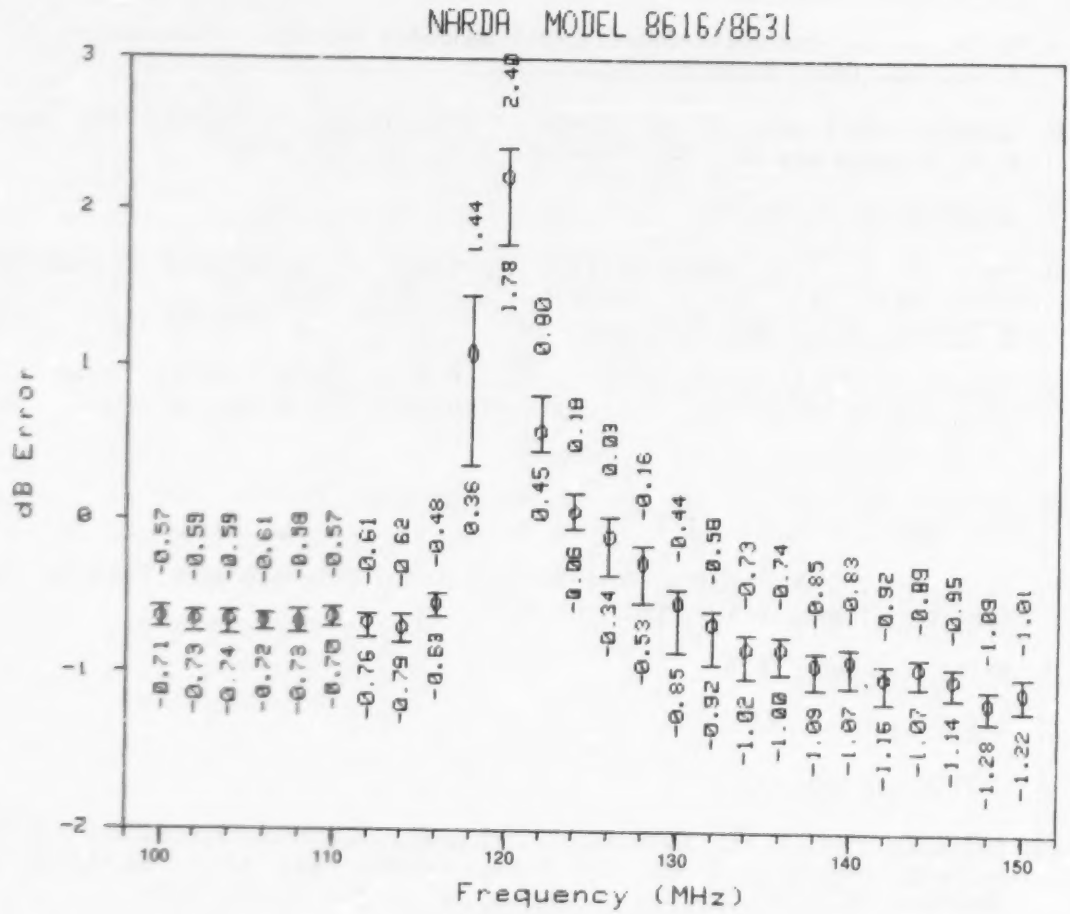


Figure 43. Modal effect in CC-101.5 cell.

REFERENCES

1. Stutzman, W. L., and Thiele, G. A. Antenna Theory and Design. John Wiley and Sons, Inc., New York, 1981.

2. Numerical Electromagnetic Code (NEC) - Method of Moments. Naval Ocean Systems Center, San Diego, CA 92152, latest revision January 1981 NOSE Technical Document 116, Vol. 2.

3. Crawford, M. L., and J. L. Workman. Using a TEM cell for EMC Measurements of Electronic Equipment. NBS Technical Note 1013, U.S. Department of Commerce, Boulder, Colorado, 1979. p. 8, Eq. (6).

4. Collin, R. E. Field Theory of Guided Waves. McGraw-Hill Book Co., New York, 1960. pp. 119-123.

5. White, J. F. The Smith Chart: An Endangered Species. Microwave J., p. 51, Eq. (21), November 1979.

6. Lorrain, Paul and D. R. Corson. Electromagnetic Fields and Waves. W. H. Freeman and Co., San Francisco 1970. pp. 566-568.

7. Crawford, p. 2, Eq.(1).

8. Weil, C. M. "The Characteristic Impedance of Rectangular Transmission Lines with Thin Center Conductor and Air Dielectric." IEEE Trans. Microwave Theory and Techniques, Vol. MTT-26(4), pp. 238-242 (April 1978).

9. Tippet, J. C. Modal Characteristics of Rectangular Coaxial Transmission Line. University Microfilms International, Ann Arbor, Michigan, 1981. p. 36.

10. Hewlett Packard. Using the Vector Impedance Meters. Application Note 86, 1968, p. 29, Eq. (1).

11. Tang, K. Y. Alternating-Current Circuits. International Textbook Co., Scranton, Pennsylvania, 1961, p. 92.

12. White, November 1979.

13. Tippet, pp. 47-52.

14. Collin, p. 120.

15. Kucia-Korniewicz, H. Comment on "Frequency Range of Large Scale TEM Mode Rectangular Strip Lines" by Weil, Joines, and Kinn; Microwave J., November 1981, pp. 93-100. Microwave J., p. 113, April 1982.

16. Tippet, Chapter VI.

17. Gruner, L. Higher Order Modes in Rectangular Coaxial Waveguides. IEEE Trans. Microwave Theory and Techniques.

18. Gruner, L. Estimating Rectangular Coax Cutoff. Microwave Journal, 22, pp. 88-92, April 1979.

19. Hill, D. A. Bandwidth Limitations of TEM Cells due to Resonances. J. of Microwave Power, 18(2), 1983.

20. Tippet, p. 123.

21. Tippet, pp. 219-223

22. Collin, p. 189, Eq. (55).

23. Reference Data for Radio Engineers, 5th Ed., Howard W. Sams and Co. Inc., 1968, Chapter 23, p. 19.

24. Brackelmann, W. Wellentypen auf der Streifenleitung mit rechteckigem Schirm. Archive Fur Electronik Und Ubertragungs-Tecknik. Vol. 21, December 1967, p. 647.

25. Sard, T. S. (Editor), R. C. Hansen and G. J. Wheeler (Co-editors), Microwave Engineers Handbook. Artech House Inc., Dedham, Mass., 1971, Vol. 1, pp. 145-147.

26. Crawford, Section 5.

27. Tippet, p. 95.

28. Bowman, R. R., Some Recent Developments in the Characterization and Measurement of Hazardous Electromagnetic Field in Biological Effects and Health Hazards of Microwave Radiation, Polish Medical Publishers, Warsaw 1974, pp. 221-222.

29. Ishii, T. K., Microwave Engineering. The Ronald Press Co., New York, 1966.

30. Hewlett Packard. High Frequency Swept Measurements. Applictions Note 183, December 1978, Apendix C.

31. Hewlett Packard. Measurement of Complex Impedance 1-1000 MHz. Application Note 77-3. April 1, 1967.

32. White, November 1979.

33. Bevington, P. R. Data Reduction and Error Analysis for the Physical Sciences. McGraw-Hill Book Co., 1969. pp. 61-62.

34. Schelkunoff, S.A., and H.T. Friis. Antennas Theory and Practice. John Wiley and Sons, Inc., New York, 1952. Chapter 10.

APPENDIX A

LOAD IMPEDANCE PROGRAM

```
10    ! "LOADZV:F"   REV 08/04/82
20    !
30    Store$=":FB,0"
40    Quote$=CHR$(34)
50    Nsamp=10
60    OUTPUT 9;"Recall time"
70    ENTER 9;A$
80    Date$=" "&A$[1;2]&"/"&A$[4;2]&"/82."
90    MASS STORAGE IS Store$
100   DEG
110   PRINTER IS 16
120   EXIT GRAPHICS
130   PRINT PAGE;"PROGRAM: LOADZV",Date$;LIN(1)
140   PRINT "    Mass Storage defaults to: ";Quote$&Store$&Quote$
150   PRINT "    Samples per meter reading: ";Nsamp;LIN(1)
160   SHORT Ckv1(8),Rho(500),U(500),V(500),A1(500),A(500),Thetac(500),R1(500),R1
170   SHORT Theta,Phi,Freqx(500),Start,Stop,Inc,Freq,Rho_t,Theta_t,Swr,X1(500),X
1
180   SHORT Size
190   DIM Meas$(1:3)[55],A$[65],Z$[40],Title$[80]
200   INTEGER Ch,Ck
210   MAT READ Ckv1
220   DATA .1,.3,1,3,10,30,100,300,1000
230   N$=Null$
240   Dg$=CHR$(179)
250   Clrend$=CHR$(27)&"K"
260   Ch$(0)="A."
270   Ch$(1)="B."
280   Meas$(1)="      S H O R T   M E A S U R E M E N T"
290   Meas$(2)="T E R M I N A T I O N   M E A S U R E M E N T "
300   Meas$(3)="       L O A D   M E A S U R E M E N T"
310   C(2)=1.2                !calibration for ch #1 for the 59313A
320   C(1)=1                  !calibration for ch #2 for the 59313A
330   S=1
340   PRINT "A/D Calibration Settings"
350   PRINT "    Channel #1:";C(1);" V";TAB(25);"(PHASE)"
360   PRINT "    Channel #2:";C(2);" V";TAB(25);"(AMPLITUDE)"
370   PRINT "    Channel #4: HI-HI";TAB(25);"(PHASE UNLOCKED Light)";LIN(1)
380   INPUT "Enter the default Phase Range to use for this measurement",Phs_def
390   IF (Phs_def=6) OR (Phs_def=18) OR (Phs_def=60) OR (Phs_def=180) THEN 440
400   BEEP
410   DISP "Error in Default Phase Range...Re-enter"
420   WAIT 1500
430   GOTO 380
440 Enter_freq: Tf=500
450   Nf=0
460   Z$="R"
470   INPUT "Do you want to enter seperate frequencies or a range(S or R)",Z$
480   IF Z$[1;1]="R" THEN Range
490   IF Z$[1;1]<>"S" THEN 460
500   Z$=Null$
510   Freqx(Nf)=0
520   DISP "Enter Frequency (MHz) #";Nf+1;Z$;
530   INPUT Freqx(Nf)
540   IF Freqx(Nf)=0 THEN Exit
550   IF (Freqx(Nf)>=.01) AND (Freqx(Nf)<=2400) THEN 580
560   CALL Dcel("Specified frequency is out of range, 0<f<=2400, try again.")
570   GOTO 510
```

```
580   Nf=Nf+1
590   Z$="Press CONTinue to Exit"
600   PRINT "   Frequency @ ";Nf;" = ";Freqx(Nf-1)
610   GOTO 510
620 Range:   Inc=1
630   INPUT "Enter Start, Step, and Increment Frequencies",Start,Stop,Inc
640   IF (Start<.01) OR (Stop>2400) OR (Start>2400) OR (Stop<.01) THEN Range
650   IF ABS(Stop-Start)/Inc+1<=Tf THEN 680
660   CALL Dcol("Too many frequencies, change dimension size.")
670   GOTO Range
680   FOR Freq=Start TO Stop STEP Inc
690      Freqx(Nf)=Freq
700      Nf=Nf+1
710   NEXT Freq
720 Exit:   IF Nf>0 THEN 750
730   CALL Dcol("No frequencies defined, try again.")
740   GOTO Enter_freq
750   Tf=Nf-1
760   REDIM Freqx(Tf),Rho(Tf),U(Tf),V(Tf),A1(Tf),A(Tf),Thetac(Tf)
770   INPUT "Enter Amplitude",Ampl
780   IF Ampl>-10 THEN Ampl=-10
790   CALL Cfreq(Freqx(0))
800   CALL Setamp(Ampl)
810   Pampl=Ampl
820   INPUT "Enter a new amplitude or press CONTinue to proceed",Ampl
830   IF Ampl<>Pampl THEN 800
840   PRINT "   Amplitude: ";Ampl;" dBm"
850   LINPUT "Enter the title for the Measurement",Title$
860 Format:  IMAGE  1X,4D.DD,3X,DDZ.DD,2X,MDZ.DD,2X,Z.3D,2X,SDDZ.D,3X,DZ.3D,6X,D
Z.DD,8X,DZ.4D
870   D$="N"
880   P$=Null$
890   INPUT "Do you want to keep these XL's and RL's? (YES or NO)",D$
900   IF D$[1;1]="N" THEN 1060
910   INPUT "Enter a unique 6 character file name",F$[1;6]
920   P$=Quote$&TRIM$(F$)&Quote$
930   ASSIGN @1 TO F$,New_file
940   IF NOT New_file THEN 1010
950   Size=INT(20*Tf/256)+4
960   PRINT "File: ";P$;" will be CREATEd for storage of";Tf*5;"Numbers."
970   PRINT "Computed size is";Size;"Records."
980   CREATE F$,Size
990   ASSIGN @1 TO F$
1000  GOTO 1050
1010  D$="N"
1020  DISP "WARNING: File ";P$;" already cataloged on disk. REPLACE? (YES or
NO)"
1030  INPUT D$
1040  IF D$[1;1]="N" THEN 870
1050  PRINT @1;Title$
1060  PRINTER IS 0
1070  PRINT LIN(2);"LOADZV Run on ";Date$
1080  IF P$[1;1]=Quote$ THEN PRINT "Data will be SAVEd on: ";P$
1090  PRINT LIN(2);TAB((80-LEN(Title$))/2);Title$
1100  PRINT LIN(3);"Frequency     Rl       Xl      Rho     Theta     VSWR     Return L
oss  Mismatch Loss"
1110  PRINT "   (MHZ)     (OHMS)   (OHMS)           (Deg)                 (dB)
   (dB)"
1120  PRINTER IS 16
1130  FOR I=S TO 3
```

```
1140      DISP "Press CONTinue to begin with";N$;" measurement."
1150      PAUSE
1160      N$=" the next"
1170      PRINT PAGE;LIN(6);" Vector Voltmeter Parameters"
1180      PRINT "     Amplitude:    CH #      Range/mV:"
1190      PRINT "     Phase:    Range:        Offset/dg:"
1200      CALL Center(1,48,Meas$(I))
1210      CALL Posit(5,51,"Frequency:")
1220      CALL Posit(6,51,"Meter Val:")
1230      CALL Posit(19,1,"System Status")
1240      FOR J=0 TO 2
1250         CALL Setamp(Ampl)          !set amplitute Ampl dBm
1260         CALL Cfreq(Freqx(0))
1270         GOSUB Setprd
1280         Conv=C(Ch)/1022
1290         Ch=2^INT(Ch-1)
1300         Instr$="H"&VAL$(Ch)&"AJ"
1310         DISP "Press STOP to terminate the program."
1320         K=0
1330         Freq=Freqx(K)
1340         CALL Cfreq(Freq)
1350         CALL Posit(5,63,VAL$(Freq)&" MHz     ")
1360         WAIT 1000
1370         Rec=0
1380         Avg=0
1390         FOR Ck=1 TO Nsamp
1400            OUTPUT 706;"HBAJ"
1410            Dig=SHIFT(READBIN(706),-8)+READBIN(706)
1420            IF Dig<-1022 THEN 1480
1430               BEEP
1440               CALL Posit(20,5,"Phase unlocked...reset freq range.  ")
1450               PAUSE
1460               CALL Posit(20,5,A$)
1470            GOTO 1380
1480               OUTPUT 706 USING "#,K";Instr$
1490               Dig=SHIFT(READBIN(706),-8)+READBIN(706)
1500               Avg=Avg+Dig
1510         NEXT Ck
1520         Volts=Avg/Nsamp*Conv
1530         IF J=2 THEN 1590
1540            IF (Volts<.25) OR (Volts>1.05) THEN GOSUB Recov
1550            IF Rec THEN 1370
1560            Amp=Amp_rangex*Volts
1570            CALL Posit(6,63,VAL$(PROUND(Amp,-4))&"   ")
1580            GOTO 1640
1590         IF (Volts<-.5) OR (Volts>.5) THEN GOSUB Recov
1600         IF Rec THEN 1370
1610         Phi=Phs_offset+Phs_range*2*Volts
1620         CALL Ckang(Phi)
1630         CALL Posit(6,63,VAL$(PROUND(Phi,-3))&Dg$&"    ")
1640         IF I<>1 THEN Nn1
1650            IF J=0 THEN A1(K)=Amp
1660            IF J=1 THEN A1(K)=Amp/A1(K)
1670            IF J<>2 THEN Nnx
1680               Thetac(K)=180-Phi
1690               CALL Ckang(Thetac(K))
1700               GOTO Nnx
1710 Nn1:      IF J=0 THEN A(K)=Amp
1720         IF J=1 THEN Rho(K)=Amp/A(K)/A1(K)
1730         IF J<>2 THEN Nnx
```

```
1740            Theta=Phi+Thetac(K)
1750            CALL Chang(Theta)
1760            IF I=3 THEN Nn2
1770               U(K)=Rho(K)*COS(Theta)
1780               V(K)=Rho(K)*SIN(Theta)
1790               GOTO Nnx
1800 Nn2:       Uw=Rho(K)*COS(Theta)
1810            Vw=Rho(K)*SIN(Theta)
1820            Ut=Uw-U(K)
1830            Vt=Vw-V(K)
1840            Denom=1+Ut*Ut+Vt*Vt-2*Ut
1850            R1=(1-Ut*Ut-Vt*Vt)/Denom*50.0
1860            X1=2*Vt/Denom*50.0
1870            Rho_t=SQR(Ut*Ut+Vt*Vt)
1880            Swr=(1+Rho_t)/(1-Rho_t)
1890            Theta_t=ACS(Ut/Rho_t)*SGN(Vt)
1900            Rtn_loss=-20*LGT(Rho_t)
1910            Mismatch_loss=-10*LGT(1-Rho_t*Rho_t)
1920            IF D$[1,1]="Y" THEN PRINT #1,Freqx(K),R1,X1,Rho_t,Theta_t
1930            PRINTER IS 0
1940            PRINT USING Format,Freqx(K),R1,X1,Rho_t,Theta_t,Swr,Rtn_loss,Mism
atch_loss
1950            R1(K)=R1
1960            X1(K)=X1
1970            PRINTER IS 16
1980 Nnx:    K=K+1
1990         IF K<=Tf THEN 1330
2000      NEXT J
2010      BEEP
2020      CALL Posit(20,5,"Measurement Complete "&Clrend$)
2030      WAIT 850
2040      BEEP
2050   NEXT I
2060   A$="Y"
2070   INPUT "Do you want a plot of the results? (YES or NO)",A$[1,1]
2080   IF A$="N" THEN 2200
2090   GRAPHICS
2100   CALL Lgrid(45,55,10,-5,5,10)
2110   LORG 5
2120   FOR I=0 TO Tf
2130      PLOT R1(I),X1(I)
2140      LABEL USING "#,K","O"
2150      PLOT R1(I),X1(I)
2160   NEXT I
2170   CALL Label
2180   EXIT GRAPHICS
2190   A$="N"
2200   INPUT "Do you want to make another load measurement(YES or NO)",A$[1,1]
2210   IF A$="Y" THEN 2240
2220   S=3
2230   GOTO 850
2240   CALL Posit(20,5," *** Program Complete ***"&Clrend$)
2250   STOP
2260 Err:   BEEP
2270   CALL Posit(20,5,"Error... Invalid Entry, Re-enter data.")
2280   RETURN
2290 Recov:  CALL Posit(20,5,"Vector Voltmeter out of range..."&Clrend$)
2300   BEEP
2310   WAIT 1500
2320   Rec=1
```

```
2330 Setgpd    IF J>1 THEN 2490
2340  A$="Amplitude measurement on channel "&Ch$(J)
2350  CALL Posit(20,5,A$)
2360  CALL Posit(8,23,Ch$(J))
2370  Ck=2
2380  INPUT "Enter Amplitude range in mV?",Amp_range
2390  FOR Ck=0 TO 8
2400  IF Ckal(Ck)=Amp_range THEN 2440
2410  NEXT Ck
2420  GOSUB Err
2430  GOTO 2380
2440  Cf=1.033
2450  IF Ck/2=INT(Ck/2) THEN Cf=.98
2460  CALL Posit(8,37,VAL$(Amp_range)&"   ")
2470  Amp_rangex=Amp_range*Cf
2480  GOTO 2720
2490  Ch=1
2500  CALL Posit(8,23,"  ")
2510  CALL Posit(8,37,"      ")
2520  A$="Phase measurement."&Clrand$
2530  CALL Posit(20,5,A$)
2540  Phs_range=Phs_def
2550  LINPUT "Enter Phase meter offset",Phase$
2560  IF Phase$=Null$ THEN 2550
2570  Cpos=POS(Phase$,",")
2580  IF Cpos=0 THEN 2640
2590  Phs_range=VAL(Phase$[1,Cpos-1])
2600  Phs_offset=VAL(Phase$[Cpos+1])
2610  IF (Phs_range=6) OR (Phs_range=18) OR (Phs_range=60) OR (Phs_range=180) TH
EN 2650
2620  GOSUB Err
2630  GOTO 2540
2640  Phs_offset=VAL(Phase$)
2650  FOR Ck=0 TO 18
2660  IF ABS(Phs_offset)/10=Ck THEN 2700
2670  NEXT Ck
2680  GOSUB Err
2690  GOTO 2550
2700  CALL Posit(9,22,VAL$(Phs_range)&" ")
2710  CALL Posit(9,38,VAL$(Phs_offset)&Dg$&"    ")
2720  CALL Posit(20,5,A$)
2730  RETURN
2740  END
2741  !
2750  SUB Cfreq(SHORT F_mhz)                    !program center frequency for 8660B
2760  Hz=F_mhz*1E6
2770  T=10-LEN(VAL$(Hz))
2780  Cmd$="/"&REV$(RPT$("0",T)&VAL$(Hz))&"("
2790  OUTPUT 719;Cmd$
2800  SUBEXIT
2810  SUBEND
2811  !
2820  SUB Setamp(Amp_dbm)                       !program amplitude for 8660B
2830  N=3
2840  Amp=Amp_dbm-13
2850  IF Amp<0 THEN N=4
2860  T=N-LEN(VAL$(Amp))
2870  Cmd$=REV$(RPT$("0",T)&VAL$(ABS(Amp)))&"C"
2880  OUTPUT 719;Cmd$
2890  SUBEXIT
```

```
2900  SUBEND
2901  !
2910  SUB Posit(X,Y,Q$)                    !position cursor at X,Y and print Q$
2920  A=INT(X)-1
2930  B=INT(Y)-1
2940  PRINT USING "#,K";CHR$(27)&"&a"&VAL$(A)&"r"&VAL$(B)&"C"&Q$
2950  SUBEXIT
2960  SUBEND
2961  !
2970  SUB Ckang(SHORT Theta)
2980  IF Theta>180 THEN Theta=Theta-360
2990  IF Theta<-180 THEN Theta=Theta+360
3000  SUBEXIT
3010  SUBEND
3011  !
3020  SUB Lgrid(Xmin,Xmax,Xdiv,Ymin,Ymax,Ydiv)
3030  DEG
3040  PLOTTER IS "GRAPHICS"
3050  LORG 2
3060  CSIZE 3.3
3070  LOCATE 20,120,13,93
3080  SCALE Xmin,Xmax,Ymin,Ymax
3090  Y_corr=(Ymax-Ymin)*.04
3100  Grid_x=(Xmax-Xmin)/Xdiv
3110  Grid_y=(Ymax-Ymin)/Ydiv
3120  GRID Grid_x,Grid_y,Xmin,Ymin
3130  LORG 8
3140  LDIR 90
3150  FOR X_label=Xmin TO Xmax STEP Grid_x
3160  MOVE X_label,Ymin-Y_corr/2
3170  LABEL USING "#,K";X_label
3180  NEXT X_label
3190  LDIR 0
3200  FOR Y_label=Ymin TO Ymax+1E-6 STEP Grid_y
3210  MOVE Xmin,Y_label
3220  LABEL USING "#,DZ.D,A";Y_label," "
3230  NEXT Y_label
3240  SUBEXIT
3250  SUBEND
3251  !
3260  SUB Label
3270  DEG
3280  SETGU
3290  LORG 6
3300  MOVE 71.50,5.2
3310  LABEL USING "#,K";"Ohms"
3320  MOVE 71.50,2.5
3330  LABEL USING "#,K";"R1"
3340  MOVE 71.50,98
3350  CSIZE 4.55,9/15
3360  LABEL USING "#,K";"Load Impedance"
3370  LDIR 90
3380  CSIZE 3.3
3390  MOVE 0,50
3400  LABEL USING "#,K";"X1"
3410  MOVE 3,50
3420  LABEL USING "#,K";"Ohms"
3430  SUBEXIT
3440  SUBEND
3441  !
```

```
3450  SUB Dcol(A$)
3460  Size=LEN(A$)
3470  FOR I=0 TO Size-1
3480     DISP TAB(Size-I);A$[1;I+1]
3490     WAIT 75
3510  NEXT I
3520  FOR I=1 TO 3
3530     WAIT 350
3540     DISP
3550     WAIT 350
3560     DISP A$
3570     BEEP
3580  NEXT I
3590  WAIT 400*Size
3600  SUBEXIT
3610  SUBEND
3611  !
3620  SUB Center(X,Y,Text$)                !center Text$ on line X column Y
3630  A=INT(X)-1
3640  B=INT(Y)-1
3650  L=INT((LEN(Text$)-1)/2)
3660  PRINT USING "#,K";CHR$(27)&"&a"&VAL$(A)&"r"&VAL$(B-L)&"C"&Text$
3670  SUBEXIT
3680  SUBEND
```

APPENDIX B

SYSTEMS OPERATING PROGRAM

```
10   !              CCCCC    EEEEEE   L          L          GGGGG    OOOOO
20   !            C     C  E        L          L        G     G  O     O
30   !          C        E          L          L       G       G O       O
40   !         C         EEE        L          L       G   GG  O       O
50   !          C        E          L          L       G     G O       O
60   !            C     C  E        L          L        G     G  O     O
70   !              CCCCC    EEEEEE   LLLLLL   LLLLLL    GGGGG    OOOOO
80   !
90   !
100  !
110  !
120  ! 0.0     HPIB DEVICE ADDRESSES       Select Code 07       01/12/83
130  !
140  ! Model #   Description                                    Address Code
150  !
160  ! 2631G     HP-IB Graphics Character Printer                    01
170  ! 59313A    Analog to Digital Converter                         06
180  ! 9200      Boonton Power Meter                                 08
190  ! 436A      Power Meter S/N 1938A06579                          13
200  ! 436A      Power Meter S/N 1938A06521                          14
210  ! 59306A    Relay Actuator                                      16
220  ! 3325A     Synthesizer/Function Generator                      17
230  ! 8660B     Synthesized Signal Generator                        19
240  ! 59307A    VHF Switch                                          22
250  !
260  !
270  ! 1.0  C O M M O N,  D A T A  T Y P E  D E F I N I T I O N S  A N D
280  !
290  !                P R O G R A M  I N I T I A L I Z A T I O N
300  !
310  !
320  ! 1.1                S T O R A G E  A L L O C A T I O N
330  !
340  COM SHORT Freq(45),R1(45),X1(45),Ri,Xi,Ampgain
350  COM SHORT R1,X1,Atten,Celln,Pt,Pdbm,Pd(1),El(1),Re(1),Pmeal,Pg
360  COM INTEGER A(730),X2,Prcnt_am
370  COM Title$[80],Oper$[80],Sys$[1]
380  SHORT Freqx(500),Scale,Power,Volts,Velx,Xi,X,Samp(900),Plotdb(900)
390  SHORT Avgi(500),Errdbi(500),Pmini(500),Pmaxi(500),Xlabel(4)
400  SHORT Pre_err(500),Post_err(500),Rw(300),Rm(300),Status
410  INTEGER Npm,I,Year,B(900),Dir(900),Pxi(3),Px2(3),Pyi(3),Py2(3),Msg,Paddr
420  INTEGER Cond,M
430  DIM Units$(1:4,1)[25],Z0[50],Cell_id$[1],System$[1]
440  !
450  ! 1.2           A S S I G N M E N T  O F  V A R I A B L E S
460  !
470  READ Pd(1),Pd(0),El(1),El(0),Re(1),Re(0)
480  DATA  0.401,     0.153
490  DATA  1.39,      0.569
500  DATA 51.3,      52.0
510  READ Xlabel(0),Pxi(0),Px2(0),Pyi(0),Py2(0)
520  DATA 180,270,360,90,180,15,75,15,75,50,110,50,110,55,55,10,10,85,85,40,40
530  ! S0=CHR$(190)          ! ## May be used as squared symbol ##
540  ! S0$="^2"              ! ## Current definition for squared symbol ##
550  Esc$=CHR$(27)          ! ## ASCII code 27 used for escape sequences to
560  !                      !    2631G printer ##
570  !
580  Units$(1,0)="V"&S0$&"/m"&S0$
585  Units$(1,1)="A"&S0$&"/m"&S0$
```

```
587   Units$(2,0)="V/m"
589   Units$(2,1)="A/m"
590   Units$(3,0)="mW/cm"&S$&" electric"
600   Units$(3,1)="mW/cm"&S$&" magnetic"
610   Units$(4,0)="dBV/m"
620   Units$(4,1)="dBA/m"
630   !
640   Slen=650              ! ** Initial value for sample length **
650   Store$=":F8,0"        ! ** Default Mass Storage Device **
660   Quote$=CHR$(34)
670   Card=7                ! ** HP-IB 98034A Select Code **
680   Printer=1             ! ** Address of Printer **
690   Version$="01/12/83."
700   !
710   ! 1.3        S E T   D E F A U L T S   F O R   E X E C U T I O N
720   !
730   MASS STORAGE IS Store$
740   EXIT GRAPHICS
750   PRINTER IS 16
760   ON ERROR GOSUB Err20
770   !
780   ! 2.0              P R O G R A M   I N T R O D U C T I O N
790   !
800   CALL Time(Date$,Time$,Day$,Month$,Year,2)
810   PRINT PAGE;"PROGRAM: CELLGO                    Version: ";Version$;LIN(1)
820   PRINT "    Mass Storage defaults to: ";Quote$&Store$&Quote$
830   PRINT "    HP-IB Select Code is: ";Card
840   PRINT "    HP-IB Printer is on Address: ";Printer;LIN(1)
850   PRINT "A/D Calibration Settings"
860   PRINT "    Channel #1: 1 V";TAB(25);"Meter Output"
870   PRINT "    Channel #2: 3.5 V";TAB(25);"Meter Output"
880   PRINT "    Channel #3: 3.5 V";TAB(25);"Rotator Reading";LIN(1)
890   !
900   ! 2.1        C H E C K   S T A T U S   O F   D E V I C E S
910   !
920   ! 2.11  2631G Line Printer
930   !
940   SET TIMEOUT Card;1
950   ON INT #Card,Printer GOTO 970
960   STATUS Card,Printer;Cond
970   IF BIT(Cond,0)<>1 THEN 1000
980   DISP "NO POWER APPLIED TO 2631G PRINTER"
990   GOTO 960
1000  OUTPUT Card,Printer USING "#,K";Esc$&"n"              !turn printer on-line
1010  STATUS Card,Printer;Cond
1020  IF BIT(Cond,6) THEN 1050              !hard off-line, user must turn on-line
1030  DISP "TURN PRINTER ON-LINE "
1040  GOTO 1010
1050  OUTPUT 716;"A124B356"                        !set A/D switches to default state
1060  !
1070  ! 2.12  Probe Rotator
1080  !
1090  OUTPUT 706;"H4AJ"
1100  N=SHIFT(READBIN(706),-8)+READBIN(706)
1110  IF ABS(N)>=1 THEN 1140
1120  DISP "NO POWER APPLIED TO ROTATOR, OR OUT OF CALIBRATION."
1130  GOTO 1090
1140  OFF INT #7
1150  SET TIMEOUT 7;10000
1160  !
```

```
1170  ! 2.2     D E F I N E   M E A S U R E M E N T   P A R A M E T E R S
1180  !
1190  CALL Setamp(-90)                          !initial setting for 8660B generator
1191  OUTPUT 717 USING "#,K";"AM-30DB"
1200  !
1210  ! 2.21  Identify the Measurement
1220  !
1230  EDIT "Enter operator identification",Oper$
1240  EDIT "Enter a title for this measurement",Title$
1250  GOSUB Get_freq                            !enter frequencies into array Freq(#)
1260  !
1270  ! 2.22  Select the Attenuator System to use
1280  !
1290  System$="Y"
1300  INPUT "Enter the Attenuator System being used (Yellow or Red)",System$
1310  IF (System$="R") OR (System$="Y") THEN 1340
1320  CALL Dcol("Only Y or R are accepted responses, try again.")
1330  GOTO 1290
1340  IF (System$="R") AND (Sys$()"R") THEN LINK "RFIT",9820
1341  IF (System$="Y") AND (Sys$()"Y") THEN LINK "YFIT",9820
1350  Sys$=System$
1360  !
1370  ! 2.23  Select the TEM Cell to use
1380  !
1390  Cell_id$="S"
1400  INPUT "Enter TEM Cell (S or L)",Cell_id$[1;1]
1410  IF (Cell_id$="S") OR (Cell_id$="L") THEN 1440
1420  CALL Dcol("Only L or S are accepted responses, try again.")
1430  GOTO 1390
1440  Celln=0
1450  IF Cell_id$="L" THEN Celln=1
1460  !
1470  ! 2.24  Select the Amplifier
1480  !
1490  Amp$="D"
1500  INPUT "Are you using the Driver or Final Amplifier? (D or F)",Amp$[1;1]
1510  IF (Amp$="D") OR (Amp$="F") THEN 1540
1520  CALL Dcol("Only D or F are accepted responses, try again.")
1530  GOTO 1490
1540  Ampgain=60
1550  IF Amp$="D" THEN Ampgain=49
1560  !
1570  ! 2.3     D E F I N E   T H E   F I E L D   T O   E S T A B L I S H
1580  !
1590  ! 2.31  Select Electric or Magnetic
1600  !
1610  A=0
1620  INPUT "Do you want to set Electric(0) or Magnetic(1) field?",A
1630  IF (A=0) OR (A=1) THEN 1690
1640  CALL Dcol("Only selections 0 or 1 are allowed, try again.")
1650  GOTO 1610
1660  !
1670  ! 2.32  Select the Units to use
1680  !
1690  IF A=0 THEN DISP "Enter units: (1) "&Units$(1,0)&", (2) V/m, (3) "&Units
$(3,0)&", or (4) dBV/m";
1700  IF A=1 THEN DISP "Enter units: (1) "&Units$(1,1)&", (2) A/m, (3) "&Units
$(3,1)&", or (4) dBA/m";
1710  N=1
1720  INPUT N
```

```
1730  IF (N<1) OR (N>4) THEN 1690
1740  !
1750  ! 2.33  Select the Field and Convert to appropriate Units
1760  !
1770  DISP "Enter Desired Field in "&Units$(N,A);
1780  INPUT Valx
1781  IF (N<>4) AND ((Valx<0) OR (Valx>1.0E8)) THEN 1690
1782  IF (N=4) AND (Valx>100) THEN 1690
1800  Inval=Valx
1810  IF N=2 THEN Valx=Valx*Valx
1820  IF (N=3) AND (A=0) THEN Valx=3767*Valx
1830  IF (N=3) AND (A=1) THEN Valx=.0266*Valx
1840  IF N=4 THEN Valx=10^(Valx/20)^2
1850  INPUT "Enter Meter Full Scale Voltage",Fsvolts
1851  IF Fsvolts>5 THEN 1850
1860  DISP "Enter Meter Full Scale Field in "&Units$(N,A);
1870  INPUT Fsval
1880  IF N=4 THEN INPUT "Enter scale range in dB",Fsrange
1890  !
1900  ! 2.34  Computer Selects the proper A/D Channel
1910  !
1930  Cn=2
1940  Cnset=3.5 !Volts
1950  IF ABS(Fsvolts)>1 THEN 1980
1960  Cn=1
1970  Cnset=1 !Volts
1980  Conv=Cnset/1022
1990  Instr$="H"&VAL$(2^(Cn-1))&"AJ"      !output command to sample above channel
2000  PRINT LIN(3);"CAUTION";LIN(1)
2010  PRINT "   1. Level the Hazard Meter and,"
2020  PRINT "   2. Check the Amplifier Status Before CONTinuing."
2030  DISP "Connect meter recorder output to Ch#";Cn;". Press CONTinue when read
y."
2040  PAUSE
2050  !
2060  ! 3.0                  P R O G R A M   E X E C U T I O N
2070  !
2080  ! 3.1  I N I T I A L I Z E   E Q U I P M E N T   F O R   E X E C U T I O N
2090  !
2100  ! 3.11  Position Probe
2110  !
2120  Mdir=1
2130  OUTPUT 706;"H4AJ"
2140  Dig=SHIFT(READBIN(706),-8)+READBIN(706)
2150  IF Dig<15 THEN 2210
2160  DISP "Positioning Probe."
2170  GOTO 2130
2180  !
2190  ! 3.12  Setup CELLGO Screen
2200  !
2210 Start: DISP
2220  Gp=0
2230  GOSUB Setup_screen
2240  FOR I=0 TO Nf-1
2250  Cf=Freqz(I)
2260  CALL Fit(System$,Freqz(I))
2270  CALL Complx(A,Freqz(I),Valx)
2280  F=FNC(Cf*1E6,F$,2)
2290  Rw(I)=377*Ri/Ro(Celln)
2300  Xw(I)=377*Xi/Ro(Celln)
```

```
2310  CALL Posit(7,16,VAL$(F)&" "&F$&"    ")
2320  CALL Posit(8,55,VAL$(PROUND(Pt,-3))&" Watt  ")
2330  CALL Posit(10,25,VAL$(PROUND(Pmval,-2))&" dBm   ")
2340  CALL Posit(11,32,"              ")
2350  CALL Posit(12,33,"              ")
2360  CALL Posit(14,1,RPT$(" ",48))
2370  !
2380  ! 3.13  Computer Selects Power Meter and Frequency Synthesizer
2390  !
2400  CALL Selectpm(Npm,Nsg,Paddr,Pmval,Freqz(I))
2410  !
2420  ! 3.14  Program Frequency and Amplitude on Selected Synthesizer
2430  !
2440  IF Nsg THEN 2550
2450  OUTPUT 717;"FR"&VAL$(Freqz(I))&"MH"    ! ** CF on 3325A **
2460  OUTPUT 717;"AM"&VAL$(Pg)&"DB"
2470  CALL Readpm(Npm,Paddr,Power,Status)     ! ** Set Amplitude to calculated
2480                                          !    setting from SUB Fit **
2490  Pg=Pg+(Pmval-Power)
2500  IF ABS(Power-Pmval))>.02 THEN 2460
2510  OUTPUT 717;"FR"
2520  GOTO 2770
2530  !
2550  CALL Cfreq(Freqz(I))                    ! ** CF on 8660B **
2560  High=Low=0                              ! ** Set Amplitude to calculated
2570                                          !    setting from SUB Fit **
2571  CALL Setam(0)
2580  CALL Setamp(INT(Pg))
2590  CALL Readpm(Npm,Paddr,Power,Status)
2600  DISP "       Setting Power Meter: ";Power;"   (Coarse)"
2601  IF High AND Low THEN Fine
2610  IF Power)=Pmval THEN 2640
2620  Pg=Pg+1
2621  High=1
2630  GOTO 2580
2640  IF High THEN Fine
2645  Pg=Pg-1
2650  Low=1
2660  GOTO 2580
2670 Fine: High=99
2671  Low=0
2680  X2=(High+Low)/2
2690  CALL Setam(X2)
2700  CALL Readpm(Npm,Paddr,Power,Status)
2705  DISP "       Setting Power Meter: ";Power;"      (Fine)  "
2710  IF (ABS(Pmval-Power)(.03) OR (ABS(High-Low)(2) THEN 2770
2720  IF Power)Pmval THEN Low=X2
2721  IF Power(Pmval THEN High=X2
2730  GOTO 2680
2740  !
2750  ! 3.2  R O T A T E   P R O B E   A N D   S A M P L E   R E S P O N S E
2760  !
2770  Pre_err(I)=PROUND(Power-Pmval,-2)
2780  CALL Posit(11,33,VAL$(Pre_err(I))&" dB   ")
2790  CALL Posit(14,1,"Field Established in Cell: "&VAL$(Inval)&" "&Units$(N,A))
2800  DISP "       Sampling data from rotation."
2810  IF Mdir>0 THEN OUTPUT 716;"B4A6"                          !probe clockwise
2820  IF Mdir<0 THEN OUTPUT 716;"B6A4"                  !probe counter-clockwise
2830 REDIM Dir(Slen),B(Slen),Plotdb(Slen)                   !redimension arrays
2840  MAT Dir=ZER
```

```
2850  MAT B=ZER
2860  !
2870  ! 3.21  Sample Data from Hazard Probe and Rotator Box
2880  !
2890  FOR J=0 TO Slen
2900  OUTPUT 706;Instr$                                    !A/D Channel for Probe
2910  B(J)=SHIFT(READBIN(706),-8)+READBIN(706)
2920  OUTPUT 706;"H4AJ"                                    !A/D Channel for Rotator Position
2930  Dir(J)=SHIFT(READBIN(706),-8)+READBIN(706)
2940  NEXT J
2950  !
2960  ! 3.22  Check for Power Meter Drift
2970  !
2980  CALL Readpm(Npm,Paddr,Power,Status)
2990  Post_err(I)=PROUND(Power-Pmval,-2)
3000  CALL Posit(12,34,VAL$(Post_err(I))&" dB    ")
3010  Mdir=-Mdir
3020  IF ABS(Post_err(I))).1 THEN 2250
3030  Power=0
3040  Setdb=10*LGT(Valx)
3050  !
3060  ! 3.23  Determine Array Length and Check for Errors
3070  !
3080  FOR J=Slen-1 TO 500 STEP -1
3090  IF ABS(Dir(J)-Dir(J+1)))>5 THEN 3150
3100  IF B(J)<=0 THEN Err21
3110  NEXT J
3120 Err19:  DISP "System Malfunction  Check rotator connections."
3130  PAUSE
3140  GOTO 2560
3150  IF J<Slen-2 THEN 3190
3160 Err18:  DISP "Program Malfunction  Sample size larger than";Slen
3170  PAUSE
3180  GOTO 2560
3190  Samp_size=J
3200  Slen=Samp_size+40
3210  !
3220  ! 3.24  Convert Values to Plotting Units
3230  !
3240  REDIM Dir(Samp_size),B(Samp_size),Plotdb(Samp_size)
3250  DISP "      Converting values for plotting. (Sample =";Samp_size;")"
3260  IF N<>4 THEN 3330
3270  FOR J=0 TO Samp_size
3280  Tmp=Fsval-Fsrange+B(J)*Conv/Fsvolts*Fsrange
3290  Plotdb(J)=Tmp-Setdb
3300  Power=Power+10^(Tmp/20)^2
3310  NEXT J
3320  GOTO 3450
3330  Chv=1
3340  IF (N=3) AND (A=0) THEN Chv=3767
3350  IF (N=3) AND (A=1) THEN Chv= 0266
3360  FOR J=0 TO Samp_size
3370  Tmp=B(J)*Conv/Fsvolts*Fsval*Chv
3380  IF (N=3) OR (N=1) THEN Tmp=SQR(Tmp)
3390  Plotdb(J)=20*LGT(Tmp)-Setdb
3400  !
3410  ! 3.25  Sum up Powers and Compute Average
3420  !
3430  Power=Power+Tmp*Tmp
3440  NEXT J
```

```
3450  Avg=Power/Samp_size
3460  Errdb=10*LGT(Avg)-Setdb
3470  IF (N=2) OR (N=4) THEN Avg=SQR(Avg)
3480  IF N=3 THEN Avg=Avg/Chv
3490  IF N=4 THEN Avg=20*LGT(Avg)
3500  !
3510  ! 4.0            G R A P H I C S   A N D   T A B L E S
3520  !
3530  MAT SEARCH Plotdb(*),MIN;Pmin
3540  MAT SEARCH Plotdb(*),MAX;Pmax
3550  Avgi(I)=Avg
3560  Errdbi(I)=Errdb
3570  Pmini(I)=Pmin
3580  Pmaxi(I)=Pmax
3590  DISP
3600  GRAPHICS
3610  DEG
3620  LDIR 0
3630  IF Gp>0 THEN 3880
3640  PLOTTER IS "GRAPHICS"
3650  !
3660  ! 4.1            I N I T I A L I Z E   G R A P H I C S
3670  !
3680  ! 4.11  Plotting Titles
3690  !
3700  LORG 6
3710  CSIZE 4.55,7/15
3720  MOVE 60,100
3730  LABEL USING "#,K";Title$
3740  CSIZE 3.1,8/15
3750  MOVE 29,94
3760  LABEL USING "#,K";"Applied Field: "&VAL$(Inval)&" "&Units$(N,A)
3770  MOVE 93,94
3780  LABEL USING "#,K";"Meter Full Scale: "&VAL$(Fsval)&" "&Units$(N,A)
3790  IF I>0 THEN 3880
3800  !
3810  ! 4.12  Program Printer for Perforation Skip, and Dump Title
3820  !
3830  OUTPUT 701;CHR$(12)&CHR$(10)&Esc$&"&l66p56f1L"
3840  DUMP GRAPHICS #7,1;90,100
3850  !
3860  ! 4.13  Setup Plotting Parameters, and Scales
3870  !
3880  LOCATE Px1(Gp),Px2(Gp),Py1(Gp),Py2(Gp)
3890  Smin=PROUND(Pmin-.5,0)
3900  Smax=PROUND(Pmax+.5,0)
3910  SCALE 0,Samp_size,Smin,Smax
3920  FRAME
3930  LORG 4
3940  CSIZE 2.25
3950  Y_corr=(Smax-Smin)*.11              ! ** Y correction factor **
3960  X_corr=Samp_size*.13                ! ** X correction factor **
3970  Grid_x=Samp_size/4+1E-4             ! ** X Grid spacing **
3980  Grid_y=Smax-Smin-1                  ! ** Y Grid spacing **
3990  FOR J=0 TO 4                        ! ** Draw X labels **
4000  MOVE Grid_x*J,Smin-Y_corr
4010  LABEL USING "#,K";VAL$(Xlabel(J))&CHR$(179)
4020  NEXT J
4030  AXES Grid_x,Grid_y,0,Smin
4040  Mid=ABS(Pmin+Pmax)/2
```

```
4050  LORG 8
4060  FOR L=Smin TO Smax                    ! ** Draw Y labels **
4070  MOVE 0,L
4080  LABEL USING "#,MDZ,X",L
4090  NEXT L
4100  MOVE 0,Errdb
4110  DRAW Samp_size,Errdb
4120  MOVE 0,Smin
4130  IF Mdir=1 THEN 4210
4140  !
4150  ! 4.15  Plot converted data
4160  !
4170  FOR J=0 TO Samp_size
4180  PLOT Samp_size-J,Plotdb(J)
4190  NEXT J
4200  GOTO 4240
4210  FOR J=0 TO Samp_size
4220  PLOT J,Plotdb(J)
4230  NEXT J
4240  LORG 6                                ! ** Label the graph **
4250  MOVE Samp_size/2,Smax+Y_corr
4260  LABEL USING "#,K";VAL$(F)&" "&F$
4270  MOVE -X_corr,(Smin+Smax)/2
4280  LDIR 90
4290  LORG 5
4300  LABEL USING "#,K";"dB Error"
4310  Gp=Gp+1
4320  SETGU
4330  IF Gp<4 THEN 4370
4340  DUMP GRAPHICS #7,1;2.25,90
4350  IF I=7 THEN OUTPUT 701 USING "#,K";Esc$&"&l66p49f1L"
4360  Gp=0
4370  EXIT GRAPHICS
4380  NEXT I
4390  GRAPHICS
4400  DUMP GRAPHICS #7,1;2.25,90
4410  EXIT GRAPHICS
4420  !
4430  ! 4.2            P R I N T   R E P O R T   S U M M A R Y
4440  !
4450  OUTPUT 701 USING "#,K";Esc$&"&l66F"       !return printer to on-line state
4460  PRINTER IS 7,1,WIDTH(132)
4470  PRINT LIN(4);TAB((81-LEN(Title$))/2);Title$,LIN(1)
4480  PRINT Day$;" ";Month$;" ";Date$[5,2];",";Year,TAB(65);Time$,LIN(1)
4490  PRINT "Operator: ";Oper$;TAB(48);
4500  IF Celln THEN PRINT "TEM Cell: CC-101.5 (Large)"
4510  IF NOT Celln THEN PRINT "TEM Cell: CC-105 (Small)"
4520  IF Amp$="D" THEN PRINT TAB(48);"Driver Amplifier Output"
4530  IF Amp$="F" THEN PRINT TAB(48);"Final Amplifier Output"
4540  IF System$="Y" THEN PRINT TAB(48);"Running Yellow System"
4550  IF System$="R" THEN PRINT TAB(48);"Running Red System"
4560  !
4570  ! 4.21  Rotation Statistics
4580  !
4590  PRINT LIN(3);TAB(35);"Rotation Statistics",LIN(2)
4600  PRINT " Freq.     Avg. Reading     Avg. Error     Low Error     High Error    H
igh-Low Error"
4610  PRINT " (MHz)       (";Units$(N,A)[1,7],")",TAB(31),"(dB)          (dB)
    (dB)            (dB)",LIN(1)
4620  FOR I=0 TO Nf-1
```

```
4630  PRINT USING 4660;Freqz(I),PROUND(Avgi(I),-3),Errdbi(I),Pmini(I),Pmaxi(I),P
maxi(I)-Pmini(I)
4640  NEXT I
4650  PRINT LIN(1);"Applied Field = ";PROUND(Inval,-3);Units$(N,A)
4660  IMAGE DDD.DDD,4X,SDZ.DDD,5X,MDZ.DD,8X,MDZ.DD,7X,MDZ.DD,10X,MDZ.DD
4670  !
4680  ! 4.3                    S U M M A R Y    G R A P H
4690  !
4700  Nf=Nf-1
4710  GRAPHICS
4720  PLOTTER IS "GRAPHICS"
4730  !
4740  ! 4.31  Setup Scaling, and Plotting Limits
4750  !
4760  LOCATE 20,120,10,93
4770  MAT SEARCH Freqz(*),MIN,Fmin
4780  MAT SEARCH Freqz(*),MAX,Fmax
4790  MAT SEARCH Pmini(*),MIN,Smin
4800  MAT SEARCH Pmaxi(*),MAX,Smax
4810  Smin=PROUND(Smin-.5,0)
4820  Smax=PROUND(Smax+.5,0)
4830  IF Nf>0 THEN Fc=(Fmax-Fmin)/Nf
4840  IF Nf=0 THEN Fc=Fmax/2
4850  Fmin=Fmin-Fc
4860  Fmax=Fmax+Fc
4870  IF Fmin=Fmax THEN 5400
4880  SCALE Fmin,Fmax,Smin,Smax
4890  FRAME
4900  CSIZE 2.55
4910  Y_corr=(Smax-Smin)*.02
4920  X_corr=(Fmax-Fmin)*.02
4930  CLIP Fmin-X_corr,Fmin,Smin,Smax
4940  AXES Fc,1,Fmin,Smin
4950  UNCLIP
4960  LORG 8
4970  FOR I=Smin TO Smax                    ! ** Label the Y axis **
4980  MOVE Fmin-X_corr*2,I
4990  LABEL USING "#,MDZ";I
5000  NEXT I
5010  IF Nf>15 THEN X_corr=0
5020  FOR I=0 TO Nf                         ! ** Draw a Box Plot of error limits **
5030  LORG 5
5040  LDIR 0
5050  MOVE Freqz(I),Smin-Y_corr
5060  DRAW Freqz(I),Smin
5070  MOVE Freqz(I),Smin-Y_corr*2
5080  IF Nf>20 THEN CSIZE 2.20
5090  LABEL USING "#,K";Freqz(I)
5100  LINE TYPE 10
5110  IF Nf>20 THEN CSIZE 2.55
5120  MOVE Freqz(I),Pmini(I)
5130  DRAW Freqz(I),Pmaxi(I)
5140  DRAW Freqz(I),Pmini(I)
5150  LINE TYPE 1
5160  !
5170  ! 4.32  Mark the Average Error with a Circle
5180  !
5190  MOVE Freqz(I),Errdbi(I)
5200  LABEL USING "#,K";"O"
5210  IF Nf<16 THEN 5270
```

```
5220  !
5230  ! 4.33  Label the Plot and Dump it to the Graphics Printer
5240  !
5250  LDIR 90
5260  LORG 2
5270  MOVE Freqz(I)-X_corr,Pmaxi(I)+Y_corr
5280  LABEL USING "#,MDZ.DD";Pmaxi(I)
5290  MOVE Freqz(I)-X_corr,Pmini(I)-Y_corr
5300  IF Nf>15 THEN LORG 8
5310  LABEL USING "#,MDZ.DD";Pmini(I)
5320  NEXT I
5330  CALL Label("Frequency (MHz)","dB Error",Title$)
5340  PRINT PAGE
5350  DUMP GRAPHICS #7,1
5360  !
5370  ! 4.34  Setting Error and Wave Impedance Summary
5380  !
5390  PRINT PAGE,LIN(1),TAB((81-LEN(Title$))/2);Title$
5400  PRINT LIN(2),TAB(20);"Power Meter Setting Error and Wave Impedance";LIN(3)
5410  PRINT "                    Pre-Rotation     Post-Rotation                "
5420  PRINT "      Frequency     Setting Error    Setting Error        Rw
 Xw"
5430  PRINT "        (MHz)           (dB)             (dB)           (ohms)     (
ohms)";LIN(1)
5440  IMAGE 6X,3D.3D,6X,MDZ.DD,12X,MDZ.DD,10X,3D.3D,4X,2DZ.3D
5450  FOR I=0 TO Nf
5460  PRINT USING 5440;Freqz(I),Pre_err(I),Post_err(I),Rw(I),Xw(I)
5470  NEXT I
5480  GOSUB Get_freq
5490  GOTO Start
5500  END
5510  !
5520  ! 5.0              I N - L I N E   S U B R O U T I N E S
5530  !
5540 Get_freq: ! Enter Frequencies from the Keyboard
5550  !
5560  EXIT GRAPHICS
5570  Nf=500   !Maximum Number of Frequencies
5580  REDIM Freqz(Nf),Avgi(Nf),Errdbi(Nf),Pmini(Nf),Pmaxi(Nf),Pre_err(Nf)
5590  REDIM Post_err(Nf)
5600  CALL Enterf(Nf,Freqz(0))
5610  Tf=Nf-1
5620  REDIM Freqz(Tf),Avgi(Tf),Errdbi(Tf),Pmini(Tf),Pmaxi(Tf),Pre_err(Tf)
5630  REDIM Post_err(Tf)
5640  RETURN
5650  !
5660 Setup_screen: ! Setup the CELLGO Screen
5670  !
5680  PRINTER IS 16
5690  EXIT GRAPHICS
5700  PRINT PAGE
5710 Sub_setup: CALL Center(1,40,"TEM Cell Automatic Control System")
5720  PRINT LIN(3),Day$,"   ";Month$;" ";Date$[5,2];",";Year;TAB(65);Time$;LIN(1
)
5730  CALL Posit(6,1,"System Parameters")
5740  IF Cell=1 THEN CALL Posit(6,48,"TEM Cell: CC-101.5 (Large)")
5750  IF NOT Cell=1 THEN CALL Posit(6,48,"TEM Cell: CC-105 (Small)  ")
5760  CALL Posit(7,5,"Frequency:")
5770  CALL Posit(8,48,"Power:")
5780  CALL Posit(9,1,"Power Meter Parameters")
```

```
5790  CALL Posit(10,5,"Calculated Setting:")
5800  IF System$="Y" THEN CALL Posit(10,48,"Running Yellow System")
5810  IF System$="R" THEN CALL Posit(10,48,"Running Red System")
5820  CALL Posit(11,5,"Pre-Rotation Setting Error:")
5830  CALL Posit(12,5,"Post-Rotation Setting Error:")
5840  CALL Posit(20,1,"System Status")
5850  IF Amp$="D" THEN CALL Posit(9,48,"Driver Amplifier Output")
5860  IF Amp$="F" THEN CALL Posit(9,48,"Final Amplifier Output")
5870  RETURN
5880  !
5890  ! Miscellaneous Program Errors
5900  !
5910 Err21:  DISP "System Malfunction Check meter connections."
5920  PAUSE
5930  RETURN
5940 Err20:  DISP "Program Malfunction Program Error: ";ERRM$
5950  GOTO 5940
5960 ! END
5970  !
5980  SUB Complx(Q,SHORT Freq,Valx)!                                    !!!Complx
5990  !
6000  ! SUB Complx(Q,SHORT Freq,Valx)
6010  !      Q       (1)Magnetic/(0)Electric indicator
6020  !      Freq    Operating Frequency
6030  !      Valx    Desired Field in A^2/m^2 for Magnetic, and V^2/m^2
6040  !              for Electric
6050  !
6060  ! Returns in COMMON
6070  !      Pt      Power (Watts)
6080  !      Pmval   Desired Power Meter Reading
6090  !      Pg      Approximate Generator Power
6100  !
6110  ! Description
6120  !    Uses R1, X1, and Ro to find cell center impedance Ri and Xi
6130  !    Also uses field equations to determine operating power (Pt) from
6140  !    desired field (Valx) and uses attenuation (Atten) to determine
6150  !    power meter setting (Pmval).
6160  !
6170  COM SHORT Freq(45),R1(45),X1(45),Ri,Xi,Ampgain
6180  COM SHORT R1,X1,Atten,Celln,Pt,Pdbm,Pd(1),El(1),Ro(1),Pmval,Pg
6190  RAD
6200  Xo=0                                  !Cell Modeled as Lossless Transmission Line
6210  Ro=Ro(Celln)
6220  Leng=El(Celln)
6230  D=Pd(Celln)
6240  X=2*PI*Leng
6250  Beta_length=X*Freq/300
6260  A=COS(Beta_length)
6270  B=SIN(Beta_length)
6280  Denom=(Ro*A-X1*B)^2+(Xo*A+R1*B)^2
6290  F=((A*R1-Xo*B)*(Ro*A-X1*B)+(X1*A+Ro*B)*(Xo*A+R1*B))/Denom
6300  G=((X1*A+Ro*B)*(Ro*A-X1*B)-(A*R1-Xo*B)*(Xo*A+R1*B))/Denom
6310  Ri=Ro*F-Xo*G
6320  Xi=Xo*F+Ro*G
6330  Tmp=Valx*Ri*D*D
6340  IF Q=1 THEN Pt=1.42129*Tmp/(Ro*Ro)! ** Magnetic **
6350  IF Q=0 THEN Pt=Tmp/(Ri*Ri+Xi*Xi) ! ** Electric **
6360  Pdbm=10*LGT(Pt*1000)
6370  Pmval=Pdbm-Atten
6380  Pg=Pdbm-Ampgain
```

```
6390  SUBEXIT
6400  SUBEND
6410  !
6420  SUB Dcol(A$)!                                                    ***Dcol
6430  !
6440  ! SUB Dcol(A$)
6450  !     A$      String to Display
6460  !
6470  Size=LEN(A$)
6480  FOR I=0 TO Size-1
6490     DISP TAB(Size-I);A$[1,I+1]
6500     WAIT 75
6510  NEXT I
6520  FOR I=1 TO 3
6530     WAIT 350
6540     DISP
6550     WAIT 350
6560     DISP A$
6570     BEEP
6580  NEXT I
6590  WAIT 40*Size
6600  SUBEXIT
6610  SUBEND
6620  !
6630  SUB Cfreq(SHORT F_mhz)!                                          ***Cfreq
6640  !
6650  ! SUB Cfreq(SHORT F_mhz)
6660  !       F_mhz     Frequency in MHz
6670  !
6680  ! Description
6690  !       Set the Center Frequency on the 8660B
6700  !
6730  Cmd$=VAL$(1E-10*INT(F_mhz*1E6))
6740  OUTPUT 719;"/I"&REV$(Cmd$[2])&"("
6750  SUBEXIT
6760  SUBEND
6770  !
6780  SUB Setamp(Amp_dbm)!                                             ***Setamp
6790  !
6800  ! SUB Setamp(Amp_dbm)
6810  !     Amp_dbm     Amplitude in dBm
6820  !
6830  ! Description
6840  !     Set the Amplitude on the 8660B to Amp_dbm
6850  !
6870  Amp$=VAL$(ABS(1E-3*(Amp_dbm-13)))&"000"
6900  Cmd$="/"&REV$(Amp$[2,4])&"C"
6910  OUTPUT 719;Cmd$
6920  SUBEXIT
6930  SUBEND
6940  !
6950  SUB Posit(X,Y,Q$)!                                               ***Posit
6960  !
6970  ! SUB Posit(X,Y,Q$)
6980  !     X,Y   Line and Column on the 9845 Screen
6990  !     Q$    String to Display at that Position
7000  !
7010  A=INT(X)-1
7020  B=INT(Y)-1
7030  PRINT USING "#,K";CHR$(27)&"&a"&VAL$(A)&"r"&VAL$(B)&"C"&Q$
```

```
7040  SUBEXIT
7050  SUBEND
7060  !
7070  SUB Center(X,Y,Text$)!                                          !!!Center
7080  !
7090  ! SUB Center(X,Y,TEXT$)
7100  !     X,Y   Line and Column Position to center Text$
7110  !     Text$ String to Display
7120  !
7130  A=INT(X)-1
7140  B=INT(Y)-1
7150  L=INT((LEN(Text$)-1)/2)
7160  PRINT USING "@,K",CHR$(27)&"&a"&VAL$(A)&"r"&VAL$(B-L)&"C"&Text$
7170  SUBEXIT
7180  SUBEND
7190  !
7200 Selectpm:
7210  SUB Selectpm(INTEGER Npm,Nsg,Paddr,SHORT Pmval,Freq)!           !!!Selectpm
7220  !
7230  ! SUB Selectpm(INTEGER Npm,Nsg,Paddr,SHORT Pmval,Freq)
7240  !     Npm    Number of the Power Meter
7250  !     Nsg    Number of the Signal Generator
7260  !     Paddr  HP-IB Adress of the Power Meter
7270  !     Pmval  Power Meter Value from Complx
7280  !     Freq   Operating Frequency
7290  !
7300  ! Description
7310  !     Based upon the Frequency (Freq) and the Power Meter Value (Pmval)
7320  !     either the Boonton or HP Power Meters are used to measure the
7330  !     and determine the establish field.  The Signal Generator is also
7340  !     selected to provide for the proper frequency source.
7350  !
7360  Npm=0                                                          !HP power meters
7370  Paddr=713
7380  IF Freq<10 THEN Npm=1                                  !select BOONTON power meter
7390  IF (Npm=0) AND (Pmval)=-20) THEN OUTPUT 716;"B1A2"
7400  IF (Npm=0) AND (Pmval(-20) THEN OUTPUT 716;"A1B2"
7410  IF (Npm=0) AND (Pmval(-20) THEN Paddr=714
7420  IF Npm THEN OUTPUT 716;"A12"
7430  IF Npm THEN OUTPUT 708;"D-70L2SH"
7440  Nsg=1
7450  IF Freq(=20 THEN Nsg=0
7460  IF Nsg THEN OUTPUT 722;"A2"       ! ## 8660B ##
7470  IF NOT Nsg THEN OUTPUT 722;"A1"   ! ## 3325A ##
7480  SUBEXIT
7490  SUBEND
7500  !
7510  SUB Setam(INTEGER Prcnt)!                                        !!!Setam
7520  !
7530  ! SUB Setam(INTEGER Prcnt)
7540  !     Prcnt    Setting for 8660B Percent Amplitude Modulation
7550  !
7560  P$=VAL$(ABS(Prcnt))
7570  IF LEN(P$)(2 THEN P$="0"&P$
7580  Cmd$="4@$"&REV$(P$)&"Z"
7590  OUTPUT 719;Cmd$
7600  SUBEXIT
7610  SUBEND
7620  !
7630  SUB Readpm(INTEGER Npm,Paddr,SHORT Power,Status)!                !!!Readpm
```

```
7640  !
7650  ! SUB Readpm(INTEGER Npm,Paddr,SHORT Power,Status)
7660  !      Power   Value read from the Power Meter
7670  !      Status  Power Meter Status
7680  !
7690  IF Npm THEN 7720
7700  CALL Readhp(Power,Paddr)          ! ** Npm=0, Read HP Meter **
7710  SUBEXIT
7720  CALL Readb(Power,Status)          ! ** Npm=1, Read Boonton Meter **
7730  SUBEXIT
7740  SUBEND
7750  !
7760  SUB Time(Date$,Time$,Day$,Month$,INTEGER Year,Type)!                  ***Time
7770  !
7780  ! SUB Time(Date$,Time$,Day$,Month$,INTEGER Year,Type)
7790  !      Date$    The current Date in the form " YY/MM/DD."
7800  !      Time$    The current Time in the form " HH.MM.SS." when Type=1
7810  !               or "HH:MM xM" when Type=2
7820  !      Day$     The day of the week
7830  !
7840  DIM Day$(6)[9],Month$(1:12)[9]
7850  INTEGER Month,Day,Hour,Minute,Sec,Weekday,Year_
7860  READ Day$(*),Month$(*)
7870  DATA Saturday,Sunday,Monday,Tuesday,Wednesday,Thursday,Friday
7880  DATA January,February,March,April,May,June,July,August,September
7890  DATA October,November,December
7900  Year=1983
7910  OUTPUT 9;"Recall time"
7920  ENTER 9;Month,Day,Hour,Minute,Sec
7930  Month$=Month$(Month)
7970  OUTPUT Date$ USING Date_format;Month,Day,Year-1900
7980  IF Type=2 THEN 8010
7990     OUTPUT Time$ USING Time_format1;Hour,Minute,Sec
8000  GOTO 8050
8010     M$="AM"
8020     IF Hour>11 THEN M$="PM"
8030     IF (Hour>12) OR (Hour=0) THEN Hour=ABS(Hour-12)
8040     OUTPUT Time$ USING Time_format2;Hour,Minute,M$
8050  Year_=Year-(Month(3)
8060  Month=Month+12*(Month(3)
8070  Year_=INT(1.25*Year_)-INT(Year_/100)+INT(Year_/400)
8080  Weekday=INT(Day+2.6*(Month+1)+Year_) MOD 7
8090  Day$=Day$(Weekday)
8110  SUBEXIT
8111  !
8112 Date_format:     IMAGE #,1X,ZZ,"/",ZZ,"/",ZZ,"."
8113 Time_format1:    IMAGE #,1X,ZZ,".",ZZ,".",ZZ,"."
8114 Time_format2:    IMAGE #,1X,DD,":",ZZ," ",AA
8115  SUBEND
8120  !
8130  DEF FNC(V,F$,Pr)!                                                     ***FNC
8140  !
8150  ! DEF FNC(V,F$,Pr)
8160  !      V    Numeric value
8170  !      F$   String equivalent
8180  !      Pr   Power Rounding Factor
8190  !
8200  ! Description
8210  !      Use internally to convert Hz to kHz, Mhz, GHz, etc.
8220  !
```

```
8230  DIM Nm$(-1:3)[3]
8240  READ Nm$(*)
8250  DATA mHz,Hz,kHz,MHz,GHz
8260  I=INT(LGT(V)/3)
8270  F$=Nm$(I)
8280  RETURN PROUND(V/10^(I*3),-Pr)
8290  FNEND
8300  !
8310  SUB Label(X$,Y$,T$)!                                          ***Label
8320  !
8330  ! SUB Label(X$,Y$,T$)
8340  !      X$   X axis label
8350  !      Y$   Y axis label
8360  !      T$   Plot label or Title
8370  !
8380  SETGU
8390  LDIR 0
8400  CSIZE 3.5
8410  LORG 6
8420  MOVE 71.5,4
8430  LABEL USING "#,K";X$
8440  MOVE 71.5,98
8450  CSIZE 4.5,6/15
8460  LABEL USING "#,K";T$
8470  DEG
8480  LDIR 90
8490  CSIZE 3.5
8500  MOVE 0,50
8510  LABEL USING "#,K";Y$
8520  SUBEXIT
8530  SUBEND
8540  !
8550  SUB Readb(SHORT Power,Status)!                                 ***Readb
8560  !
8570  ! SUB Readb(SHORT Power,Status)
8580  !      Power    Power in dBm returned from the Boonton
8590  !      Status   Boonton Power Meter Status
8600  !
8610  ! Description
8620  !      Routine to take a reading from the Boonton Power Meter,
8630  !      and allow for settling time.
8640  !
8650  DIM Err$[50]
8660  SHORT T
8670  INTEGER I
8680  FOR I=1 TO 25
8690  T=Power
8700  ENTER 708;Power,Status,Range
8710  IF I=1 THEN 8740
8720  IF ABS(T-Power)<=.01 THEN 8770
8730  WAIT 250+300*(Power<-20)*INT(ABS(Power/10))
8740  NEXT I
8750  DISP "Power Meter not Settled."
8760  PAUSE
8770  IF Status=0 THEN SUBEXIT
8780  IF Status=3 THEN Err$="Meter Underrange."
8790  IF Status=4 THEN Err$="Meter Overrange."
8800  IF Status=5 THEN Err$="Possible Hardware Malfunction."
8810  BEEP
8920  DISP "Boonton - ";Err$
```

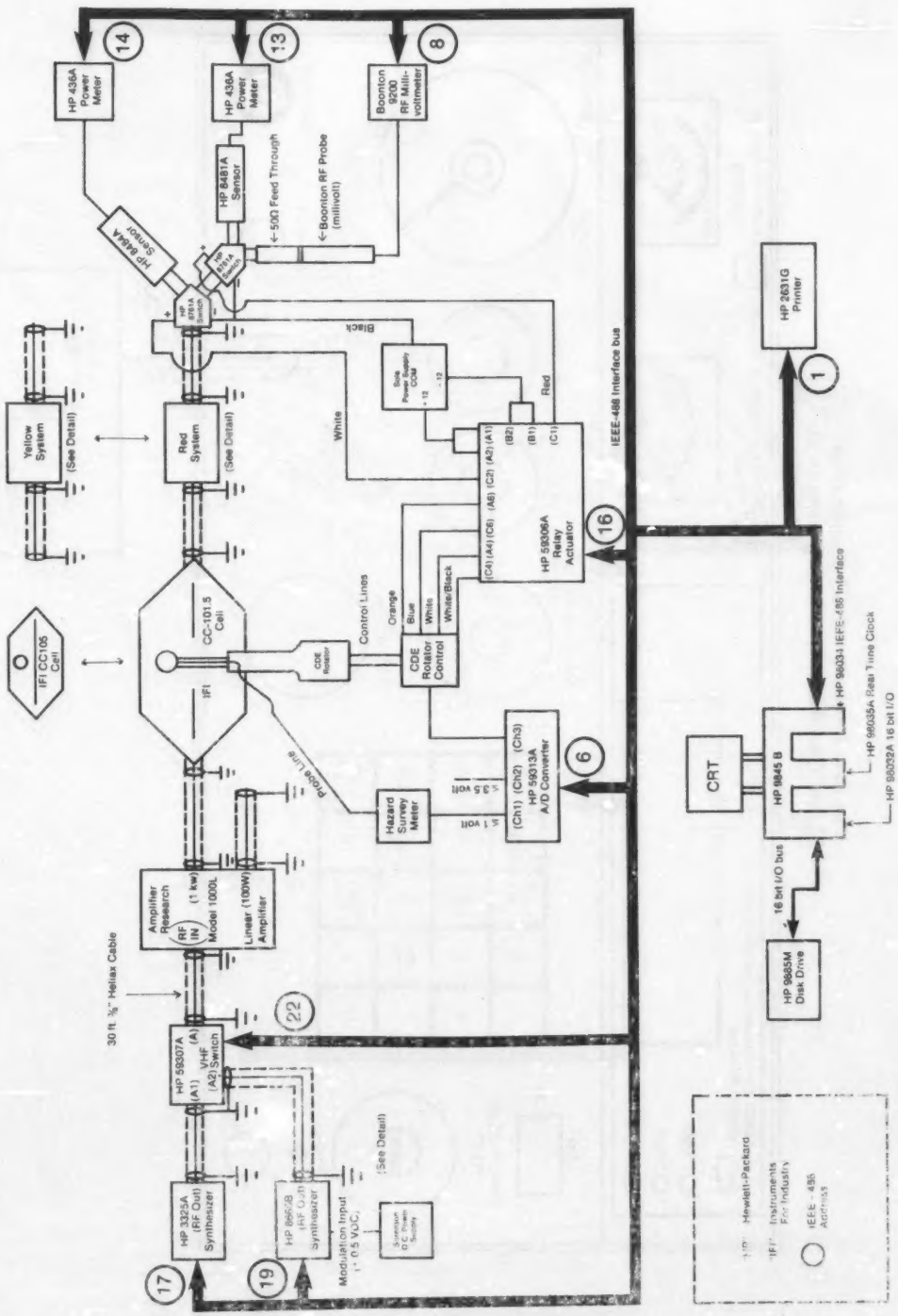
```
8830  PAUSE
8840  DISP
8850  GOTO 8680
8860  SUBEND
8870  !
8880  SUB Readhp(SHORT Power,INTEGER Paddr)!                          !!!Readhp
8890  !
8900  ! SUB Readhp(SHORT Power,INTEGER Paddr)
8910  !     Power   Power read from the HP Power Meter in dBm
8920  !     Paddr   Adress of the Power Meter
8930  !
8940  DIM Err$[65]
8950 Start: !
8960  FOR X=1 TO 20
8970     OUTPUT Paddr;"D-V"
8980     WAIT (Range=73)*4000
8990     ENTER 7,Paddr USING "B,B,X,F";Status,Range,Power
9000     IF Status=80 THEN 9090
9010        Err$="Power Meter Malfunction."
9020        IF (Status=81) OR (Status=83) THEN Err$="Meter Under Range."
9030        IF Status=82 THEN Err$="Meter Over Range."
9040        BEEP
9050        DISP "HP436A - "&Err$
9060        PAUSE
9070        DISP
9080     GOTO Start
9090     IF (X<>1) AND (ABS(Power-P1)<=.02) THEN 9130
9100        P1=Power
9110  NEXT X
9120  DISP "POWER METER NOT SETTLED"
9130  LOCAL 7,Paddr
9140  SUBEXIT
9150  SUBEND
9160  !
9170  SUB Enterf(Nfreq,SHORT Freqx(*))!                               !!!Enterf
9180  !
9190  ! SUB Enterf(Nfreq,SHORT Freqx(*))
9200  !     Nfreq    Number of Frequencies that were entered
9210  !     Freqx(*) The actual frequency values
9220  !
9230  ! Description
9240  !     Subroutine to enter frequencies from the keyboard into the program
9250  !
9260  DIM Z$[25],A$[160]
9270  PRINTER IS 16
9280 Enter_freq: Nf=0
9290  Z$="R"
9300  INPUT "Do you want to enter seperate frequencies or a range? (S or R)",Z
$
9310  IF Z$[1;1]="R" THEN Range
9320  IF Z$[1;1]<>"S" THEN 9290
9330  ON ERROR GOTO Bad_number
9340  !
9350  ! Enter frequencies Seperatly
9360  !
9370  Z$=Null$
9380  A$=Null$
9390  DISP "Enter Frequency (MHz) #";Nf+1;Z$;
9400  LINPUT A$
9410  Size=LEN(A$)
```

```
9420  IF Size=0 THEN Exit
9430  FOR I=1 TO Size
9440     C=POS(A$[I,Size],",")
9450     IF C=0 THEN 9490
9460        X=C+I-2
9470        Freqx(Nf)=VAL(A$[I,X])
9480     GOTO 9500
9490        Freqx(Nf)=VAL(A$[I])
9500     IF (Freqx(Nf)=.01) AND (Freqx(Nf)<=2400) THEN 9530
9510        CALL Dcol("Specified Frequency is out of Range, Try Again...")
9520        GOTO 9380
9530     Nf=Nf+1
9540     Z$="Press CONTinue to Exit"
9550     PRINT "   Frequency # ";Nf;" = ";Freqx(Nf-1)
9560     I=X+1
9570     IF C=0 THEN 9380
9580  NEXT I
9590  !
9600  ! Enter frequencies as a range
9610  !
9620 Range:  Inc=1
9630  INPUT "Enter Start, Stop, and Increment Frequencies (MHz)",Start,Stop,Inc
9640  IF (Start<.01) OR (Stop)2400) OR (Start)2400) OR (Stop<.01) THEN Range
9650  IF ABS(Stop-Start)/Inc+1<=Nfreq THEN 9680
9660  CALL Dcol("Too many Frequencies, Change dimension size.")
9670  GOTO Range
9680  FOR Freq=Start TO Stop STEP Inc
9690     Freqx(Nf)=Freq
9700     Nf=Nf+1
9710  NEXT Freq
9720 Exit:  IF Nf)0 THEN 9750
9730  CALL Dcol("No Frequencies Defined, Try Again...")
9740  GOTO Enter_Freq
9750  Nfreq=Nf
9760  SUBEXIT
9770 Bad_number: !
9780  IF ERRN()32 THEN 10559
9790  CALL Dcol("Illegal Numeric Response. Try Again...")
9800  GOTO 9380
9810  SUBEND
9820  SUB Fit(System$,SHORT Freqx)    !yellow system
9830  COM SHORT Freq(45),R1(45),X1(45),Ri,Xi,Ampgain
9840  COM SHORT R1,X1,Atten,Celln,Pt,Pdbm,Pd(1),E1(1),Ro(1),Pmval,Pg
9841  SHORT Rho,Theta
9842  DIM Imp_title$[160]
9850  DEF FNAtten1(SHORT X)=44.126-3.26E-2*LOG(X)
9860  DEF FNAtten2(SHORT X)=44.2+.1034*X
9870  DEF FNAtten3(SHORT X)=44.28+.03*X-.00282*X*X
9880  DEF FNAtten4(SHORT X)=44.24+.0082*X-1.4E-5*X*X
9890  IF Freq(0)()0 THEN 9990
9900  ASSIGN @1 TO "ZY1",A
9910  IF NOT A THEN 9950
9920  CALL Dcol("ZY1 is not found, please supply correct disk")
9930  PAUSE
9940  GOTO 9900
9950  DISP
9951  READ @1;Imp_title$
9960  FOR I=0 TO 45
9970  READ @1;Freq(I),R1(I),X1(I),Rho,Theta
9980  NEXT I
```

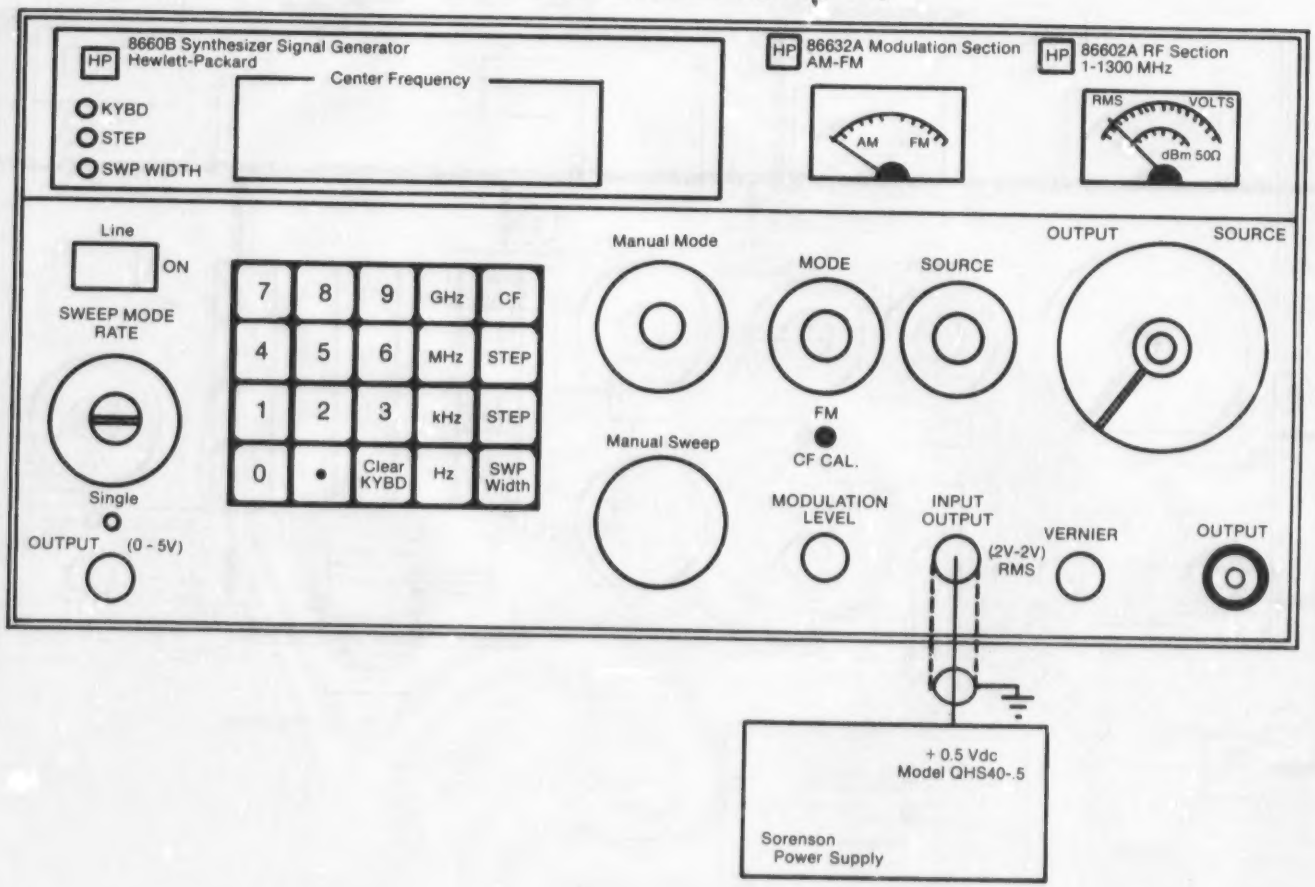
```
9990  Atten=-9E10
10000 IF (Freqx)=.01) AND (Freqx(.1) THEN Atten=FNAtten1(Freqx)
10010 IF (Freqx)=.1) AND (Freqx(1) THEN Atten=FNAtten2(Freqx)
10020 IF (Freqx)=1) AND (Freqx(10) THEN Atten=FNAtten3(Freqx)
10030 IF (Freqx)=10) AND (Freqx(=220) THEN Atten=FNAtten4(Freqx)
10040 R1=50
10050 X1=0
10060 IF (Freqx(=0) OR (Freqx)220) THEN Err
10070 IF Freqx(=1 THEN SUBEXIT
10080 FOR I=0 TO 45
10090 IF Freqx(=Freq(I) THEN 10130
10100 NEXT I
10110 Err: R1=X1=-9E10
10120 SUBEXIT
10130 Freqd=Freq(I)-Freq(I-1)
10140 Mr1=(R1(I)-R1(I-1))/Freqd
10150 Mx1=(X1(I)-X1(I-1))/Freqd
10160 Br1=R1(I)-Mr1*Freq(I)
10170 Bx1=X1(I)-Mx1*Freq(I)
10180 R1=Mr1*Freqx+Br1
10190 X1=Mx1*Freqx+Bx1
10200 SUBEXIT
10210 SUBEND
```

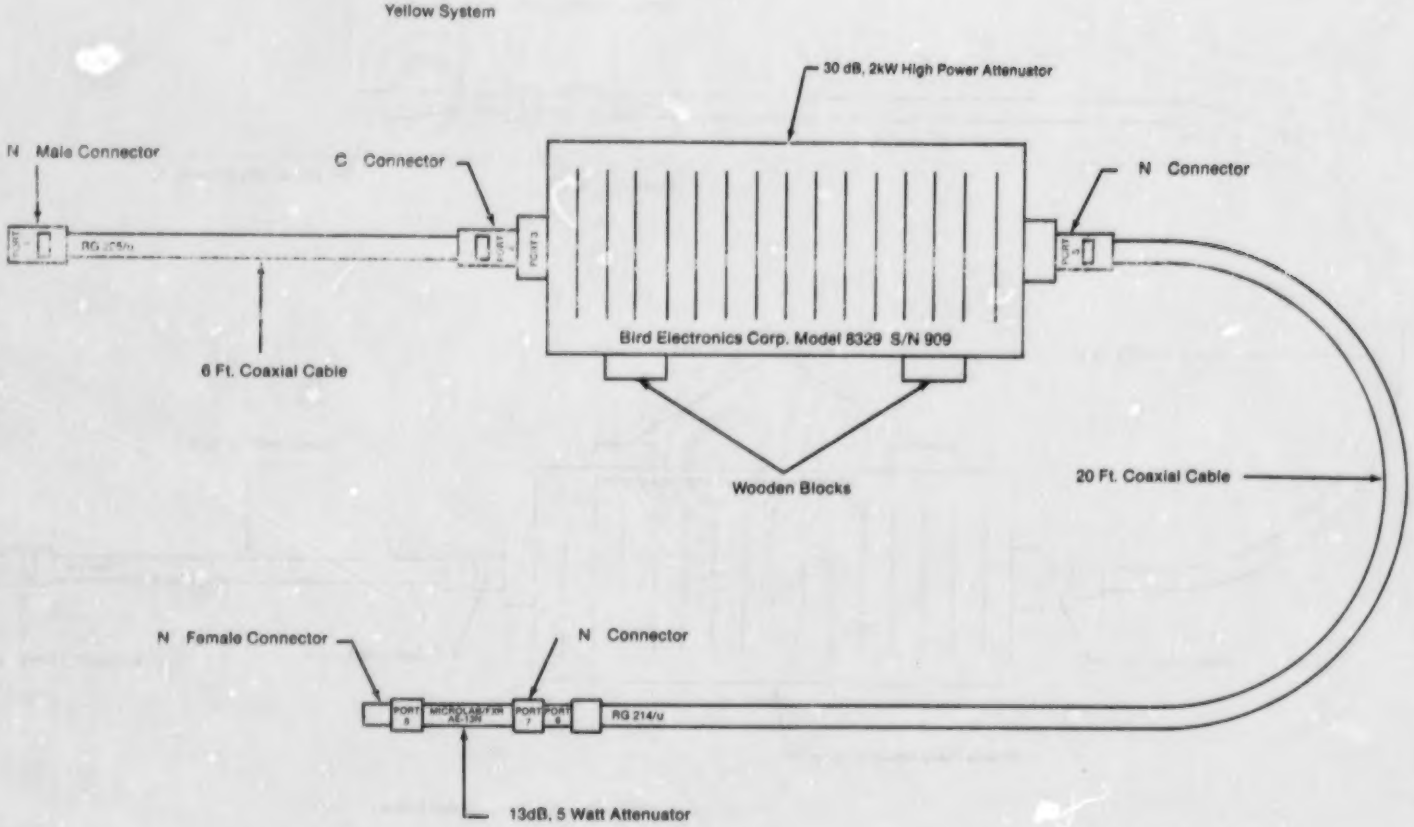
APPENDIX C

DETAILED SYSTEM DIAGRAMS

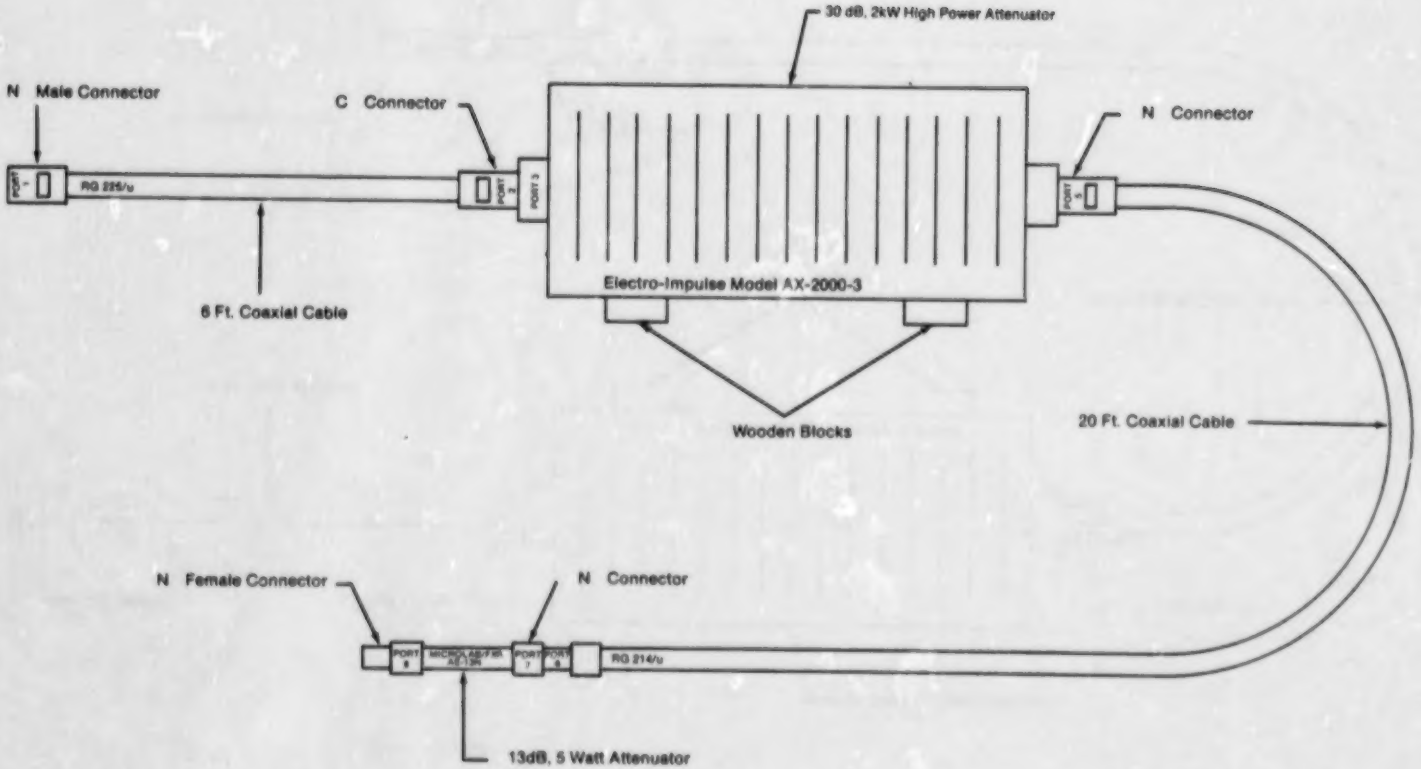


Hewlett-Packard 8660B Synthesizer
Signal Generator (Including Plug-In's)




Yellow System
30 dB, 2kW High Power Attenuator
N Male Connector
C Connector
N Connector
Bird Electronics Corp. Model 8329 S/N 909
6 Ft. Coaxial Cable
Wooden Blocks
20 Ft. Coaxial Cable
N Female Connector
N Connector
RG 214/u
13dB, 5 Watt Attenuator

Red System


30 dB, 2kW High Power Attenuator
N Male Connector
C Connector
N Connector
RG 225/u
6 Ft. Coaxial Cable
Electro-Impulse Model AX-2000-3
Wooden Blocks
20 Ft. Coaxial Cable
N Female Connector
N Connector
RG 214/u
13dB, 5 Watt Attenuator

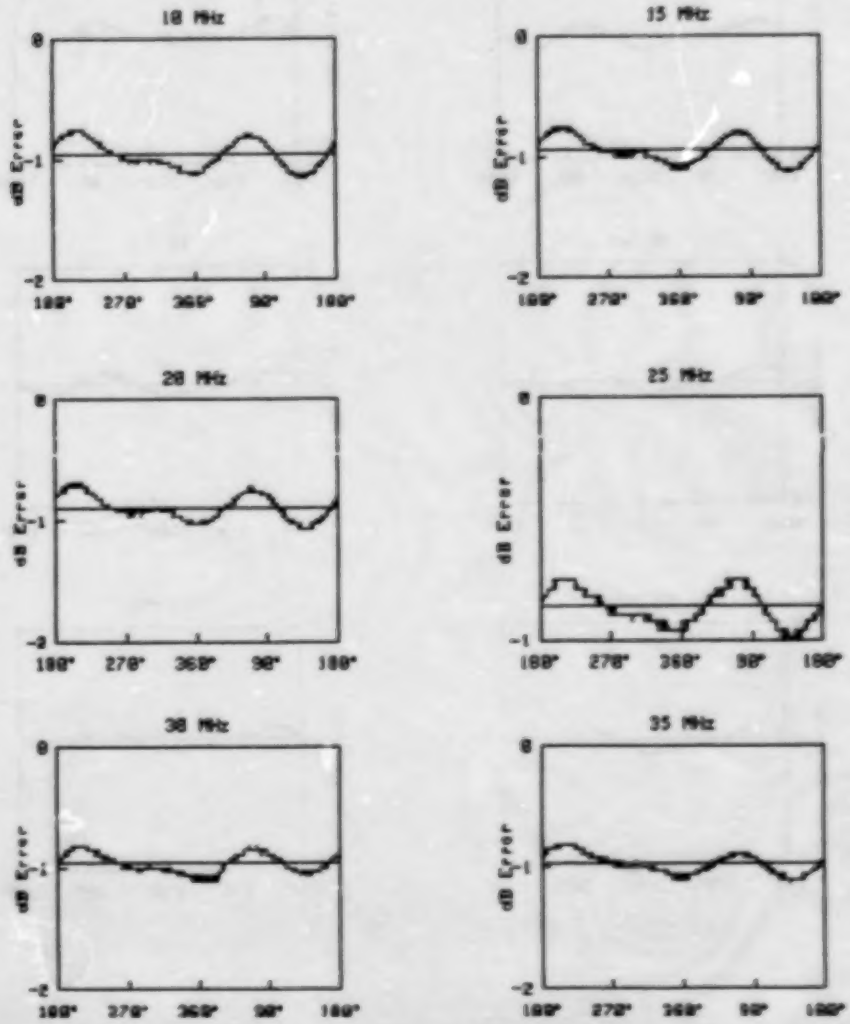
APPENDIX D

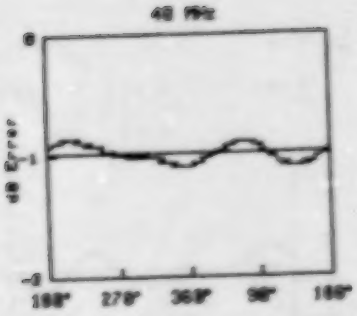
PROBE CALIBRATION RESULTS COMPARED WITH AND WITHOUT LOAD IMPEDANCE CORRECTION

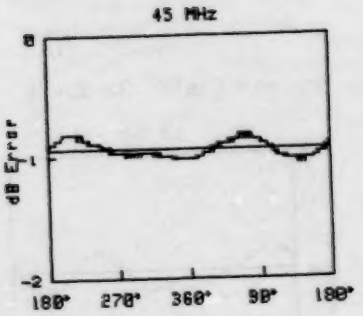
NBS EFM-5 S/N 1

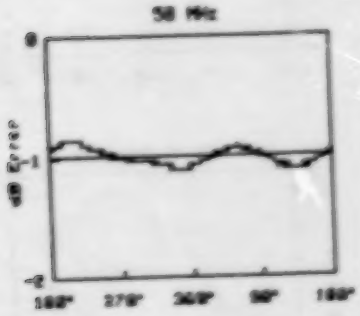
Applied Field: 30 dBV/m

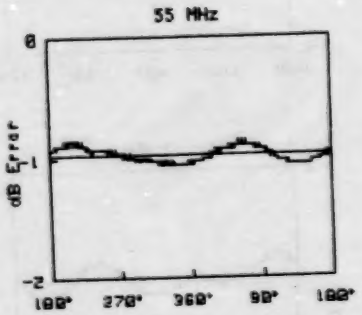
Meter Full Scale: 40 dBV/m

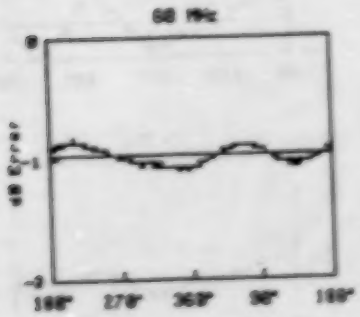


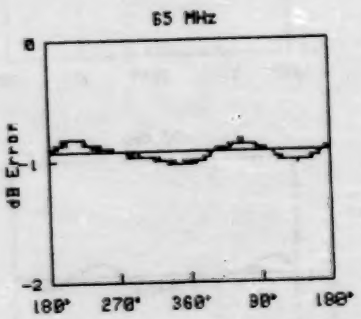

40 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

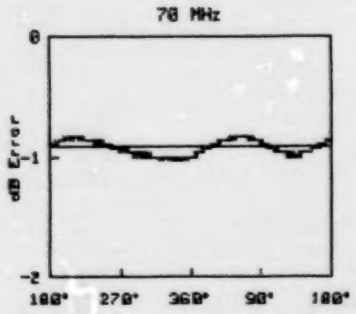

45 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

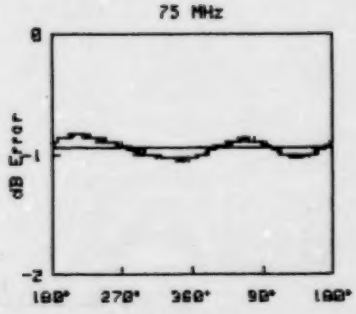

50 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

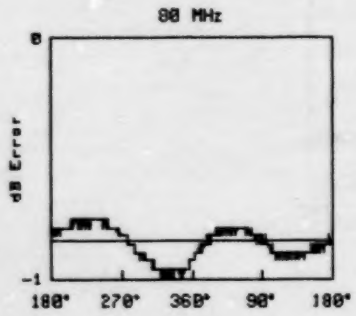

55 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

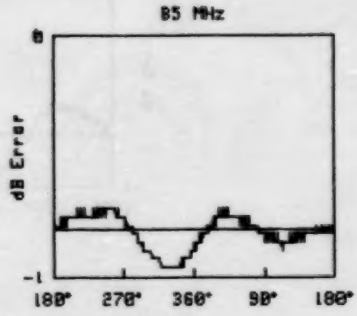

60 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

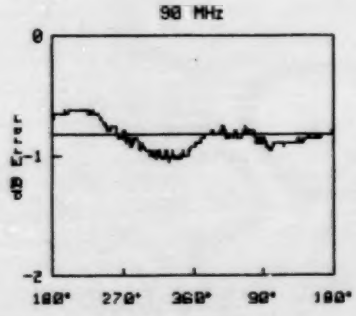

65 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

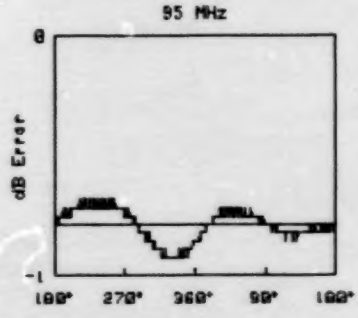

70 MHz
0
dB Error
-1
-2
180°
270°
360°
90°
180°

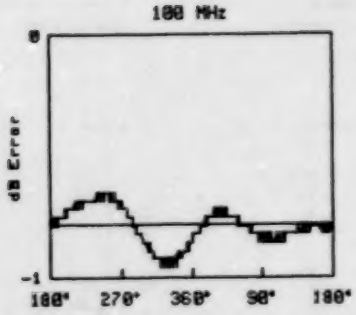

75 MHz
0
dB Error
-1
-2
180°
270°
360°
90°
180°


80 MHz
0
dB Error
-1
180°
270°
360°
90°
180°


85 MHz
0
dB Error
-1
180°
270°
360°
90°
180°


90 MHz
0
dB Error
-1
-2
180°
270°
360°
90°
180°


95 MHz
0
dB Error
-1
180°
270°
360°
90°
180°


100 MHz
0
dB Error
-1
180°
270°
360°
90°
180°

NBS EFM-5 S/N 1

Friday October 01, 1982 4:03 PM

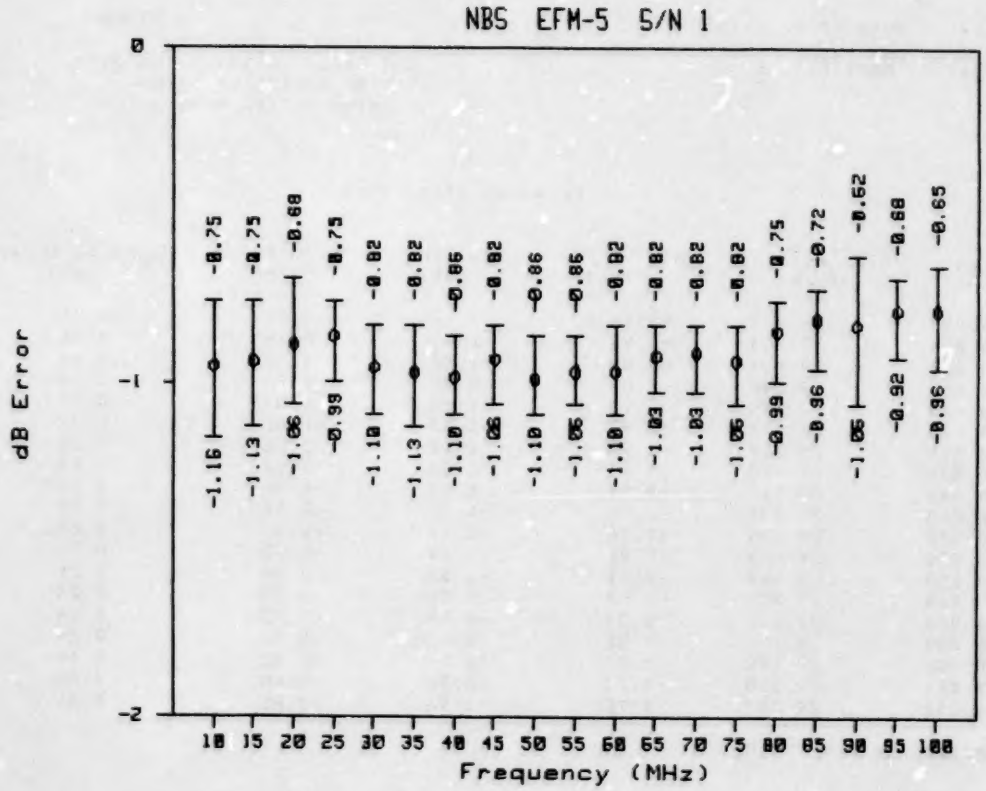
Operator: MANTIPLY, E. D.

TEM Cell: CC-101.5 (Large)
Driver Amplifier Output
Running Yellow System

Rotation Statistics

Freq. (MHz)	Avg. Reading (dBV/m)	Avg. Error (dB)	Low Error (dB)	High Error (dB)	High-Low Error (dB)
10.000	29.050	-0.95	-1.16	-0.75	0.41
15.000	29.063	-0.94	-1.13	-0.75	0.38
20.000	29.117	-0.88	-1.06	-0.68	0.38
25.000	29.142	-0.86	-0.99	-0.75	0.24
30.000	29.048	-0.95	-1.10	-0.82	0.27
35.000	29.033	-0.97	-1.13	-0.82	0.31
40.000	29.019	-0.98	-1.10	-0.86	0.24
45.000	29.072	-0.93	-1.06	-0.82	0.24
50.000	29.012	-0.99	-1.10	-0.86	0.24
55.000	29.036	-0.96	-1.06	-0.86	0.21
60.000	29.035	-0.96	-1.10	-0.82	0.27
65.000	29.080	-0.92	-1.03	-0.82	0.21
70.000	29.092	-0.91	-1.03	-0.82	0.21
75.000	29.068	-0.93	-1.06	-0.82	0.24
80.000	29.157	-0.84	-0.99	-0.75	0.24
85.000	29.192	-0.81	-0.96	-0.72	0.24
90.000	29.175	-0.83	-1.06	-0.62	0.45
95.000	29.218	-0.78	-0.92	-0.68	0.24
100.000	29.217	-0.78	-0.96	-0.65	0.31

Applied Field = 30 dBV/m


NBS EFM-5 S/N 1
dB Error
0
-1
-2
-1.16 -0.75
-1.13 -0.75
-1.06 -0.68
-0.99 -0.75
-1.10 -0.82
-1.13 -0.82
-1.10 -0.86
-1.06 -0.82
-1.10 -0.86
-1.06 -0.86
-1.10 -0.82
-1.03 -0.82
-1.03 -0.82
-1.06 -0.82
-0.99 -0.75
-0.96 -0.72
-1.06 -0.62
-0.92 -0.68
-0.96 -0.65
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Frequency (MHz)

NBS EFM-5 S/N 1

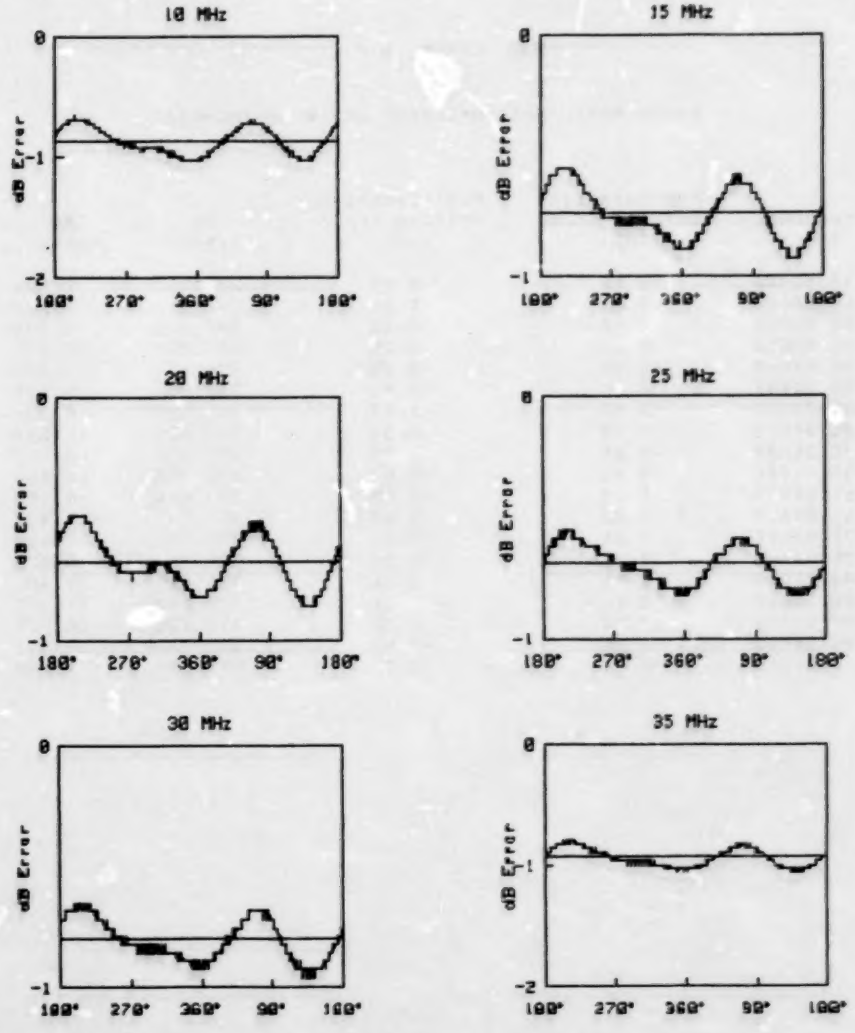
Power Meter Setting Error and Wave Impedance

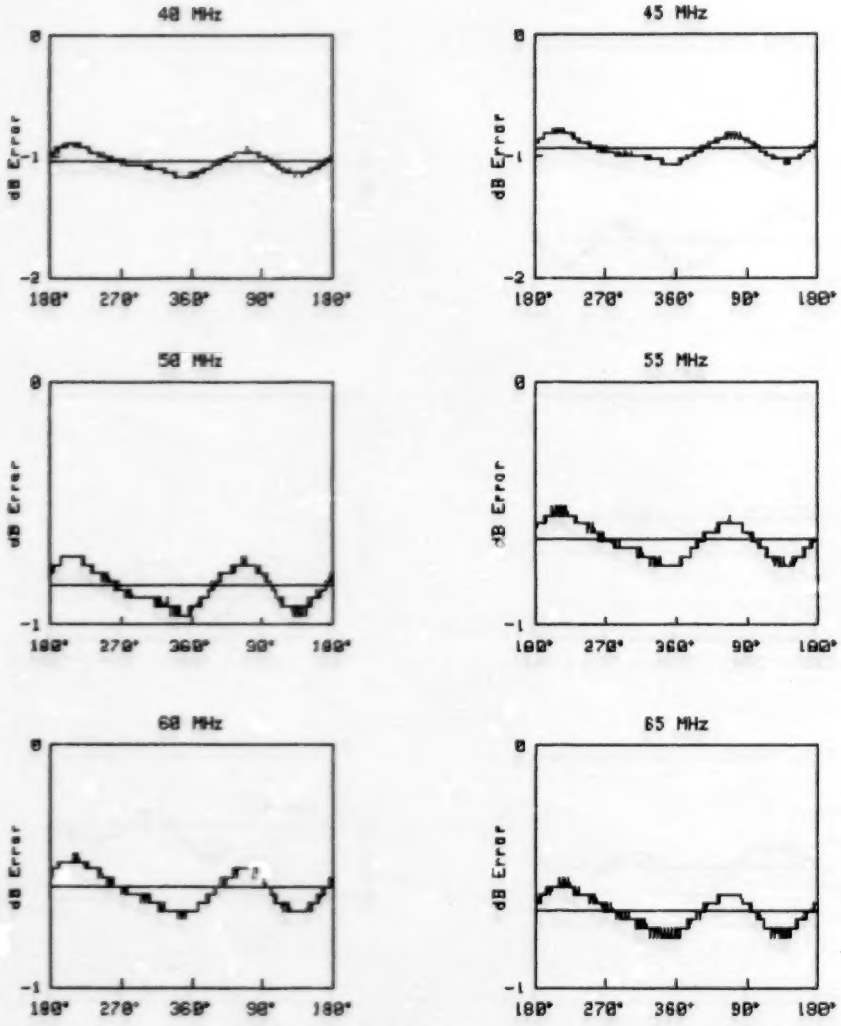
Frequency (MHz)	Pre-Rotation Setting Error (dB)	Post-Rotation Setting Error (dB)	Rw (ohms)	Xw (ohms)
10.00000	-0.01	0.04	377.913	7.271
15.00000	-0.01	0.00	383.912	5.322
20.00000	0.00	0.00	386.071	-.739
25.00000	0.02	0.05	383.928	-7.100
30.00000	-0.01	-0.05	376.633	-11.100
35.00000	0.01	-0.01	368.998	-8.179
40.00000	-0.02	-0.03	364.250	0.238
45.00000	0.00	0.00	368.025	10.556
50.00000	-0.01	0.00	379.341	18.657
55.00000	-0.01	-0.02	393.368	11.986
60.00000	0.00	-0.02	397.626	-4.085
65.00000	-0.02	0.03	387.727	-18.432
70.00000	0.01	-0.06	370.569	-19.696
75.00000	-0.02	0.00	357.968	-8.078
80.00000	-0.01	0.01	358.079	9.481
85.00000	0.01	0.01	372.200	21.897
90.00000	-0.02	0.10	392.178	18.920
95.00000	-0.01	-0.03	402.998	-.421
100.00000	-0.01	0.02	393.599	-21.109

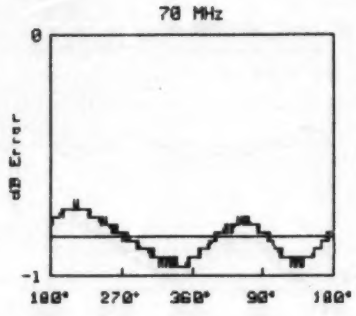
NBS EFM-5 S/N 1 Zi=Zo=50+0j

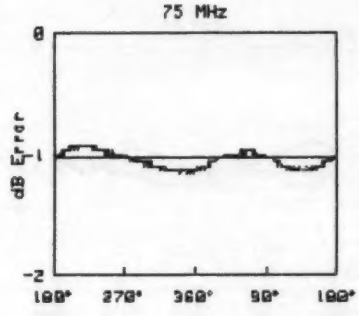
Applied Field: 30 dBV/m

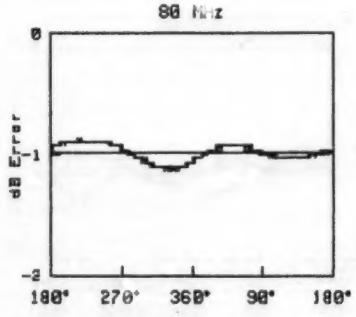
Meter Full Scale: 40 dBV/m

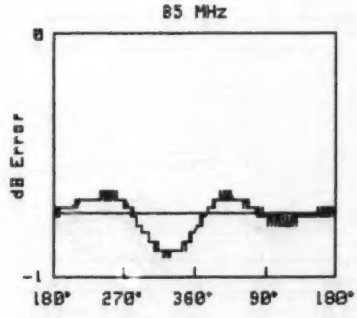


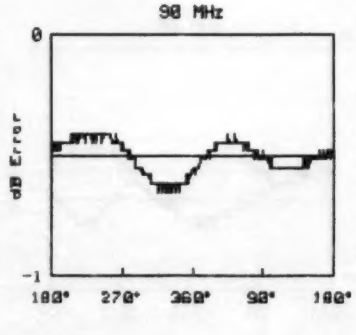

40 MHz
45 MHz
50 MHz
55 MHz
60 MHz
65 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°

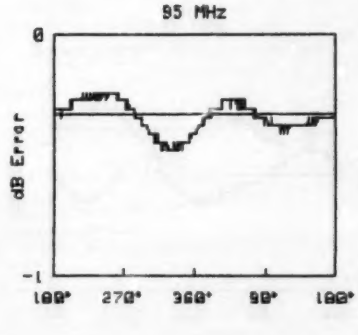

70 MHz
dB Error
0
-1
180°
270°
360°
90°
180°

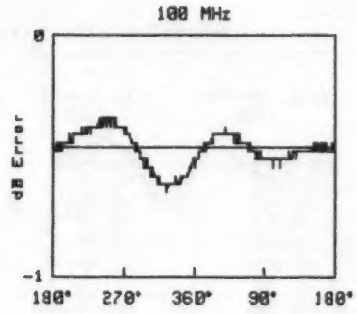

75 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°


80 MHz
dB Error
0
-1
-2
180°
270°
360°
90°
180°


85 MHz
dB Error
0
-1
180°
270°
360°
90°
180°


90 MHz
dB Error
0
-1
180°
270°
360°
90°
180°


95 MHz
dB Error
0
-1
180°
270°
360°
90°
180°


100 MHz
0
dB Error
-1
180°
270°
360°
90°
180°

NBS EFM-5 S/N 1 Zi=Zo=50+0j

Friday October 01, 1982 4:59 PM (1)

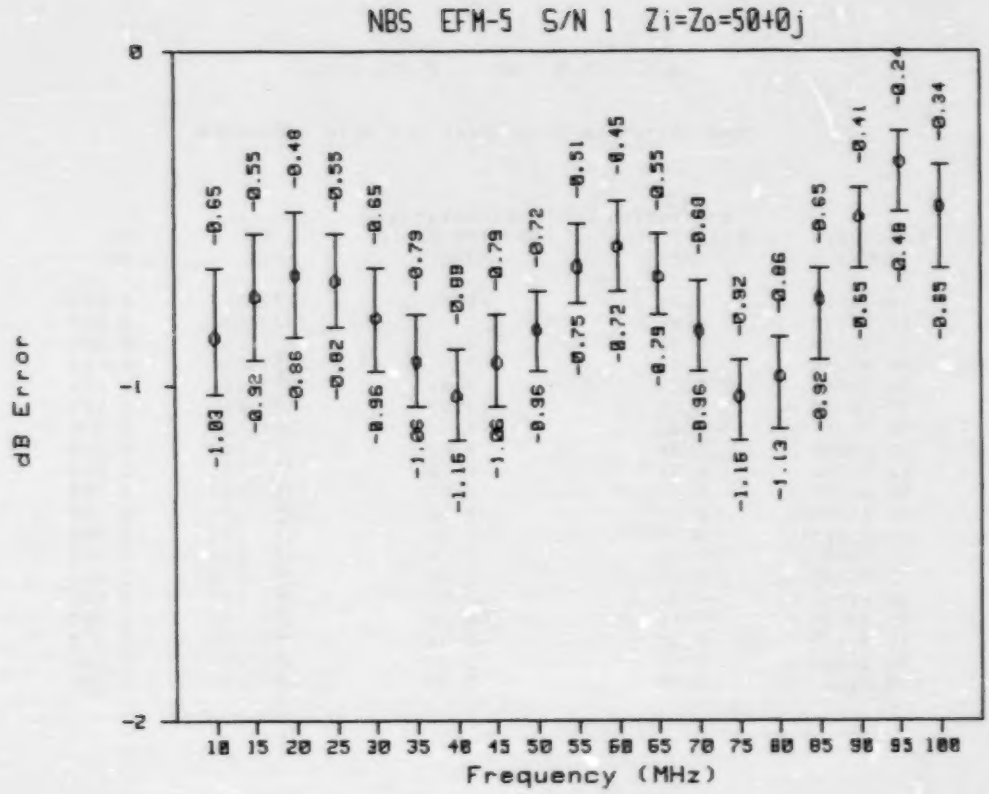
Operator: MANTIPLY, E. D.

TEM Cell: CC-101.5 (Large)
Driver Amplifier Output
Running Yellow System

Rotation Statistics

Freq. (MHz)	Avg. Reading (dBV/m)	Avg. Error (dB)	Low Error (dB)	High Error (dB)	High-Low Error (dB)
10.000	29.142	-0.86	-1.03	-0.65	0.38
15.000	29.266	-0.73	-0.92	-0.55	0.38
20.000	29.330	-0.67	-0.86	-0.48	0.38
25.000	29.313	-0.69	-0.82	-0.55	0.27
30.000	29.202	-0.80	-0.96	-0.65	0.31
35.000	29.071	-0.93	-1.06	-0.79	0.27
40.000	28.968	-1.03	-1.16	-0.89	0.27
45.000	29.068	-0.93	-1.06	-0.79	0.27
50.000	29.165	-0.84	-0.96	-0.72	0.24
55.000	29.354	-0.65	-0.75	-0.51	0.24
60.000	29.414	-0.59	-0.72	-0.45	0.27
65.000	29.323	-0.68	-0.79	-0.55	0.24
70.000	29.163	-0.84	-0.96	-0.68	0.27
75.000	28.966	-1.03	-1.16	-0.92	0.24
80.000	29.027	-0.97	-1.13	-0.86	0.27
85.000	29.258	-0.74	-0.92	-0.65	0.27
90.000	29.504	-0.50	-0.65	-0.41	0.24
95.000	29.667	-0.33	-0.48	-0.24	0.24
100.000	29.536	-0.46	-0.65	-0.34	0.31

Applied Field = 30 dBV/m


NBS EFM-5 S/N 1 Zi=Zo=50+0j
dB Error
0
-1
-2
-1.03 -0.65
-0.92 -0.55
-0.86 -0.48
-0.82 -0.55
-0.96 -0.65
-1.06 -0.79
-1.15 -0.88
-1.06 -0.79
-0.96 -0.72
-0.75 -0.51
-0.72 -0.45
-0.79 -0.55
-0.96 -0.68
-1.15 -0.92
-1.13 -0.86
-0.92 -0.65
-0.65 -0.41
-0.48 -0.24
-0.65 -0.34
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Frequency (MHz)

NBS EFM-5 S/N 1 Zi=Zo=50+0j

Power Meter Setting Error and Wave Impedance

Frequency (MHz)	Pre-Rotation Setting Error (dB)	Post-Rotation Setting Error (dB)	Rw (ohms)	Xw (ohms)
10.00000	0.01	-0.01	377.000	0.000
15.00000	0.01	0.02	377.000	0.000
20.00000	0.01	0.01	377.000	0.000
25.00000	0.00	0.03	377.000	0.000
30.00000	0.00	0.01	377.000	0.000
35.00000	0.00	0.03	377.000	0.000
40.00000	-0.02	-0.02	377.000	0.000
45.00000	0.00	0.02	377.000	0.000
50.00000	-0.01	-0.03	377.000	0.000
55.00000	0.00	0.00	377.000	0.000
60.00000	0.01	0.02	377.000	0.000
65.00000	-0.02	0.01	377.000	0.000
70.00000	-0.01	0.01	377.000	0.000
75.00000	-0.01	-0.02	377.000	0.000
80.00000	-0.01	-0.01	377.000	0.000
85.00000	-0.01	0.00	377.000	0.000
90.00000	-0.01	-0.01	377.000	0.000
95.00000	0.01	0.02	377.000	0.000
100.00000	0.00	-0.01	377.000	0.000